AN ENVIRONMENTAL SKIN:
Enhancing Thermal Performance with Double-Skin Façades in Hawai`i's Climate.

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Submitted towards the fulfillment of the requirements for the Doctor of Architecture degree.

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We certify that we read this Doctorate Project and that, in our opinion, it is satisfactory in scope and quality in partial fulfillment for the degree of Doctor of Architecture in the School of Architecture, University of Hawai'i at Mānoa.

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ABSTRACT

Highly glazed commercial buildings in Hawai`i present overheating challenges due to high outside temperatures combined with solar gains. In order to optimize thermal performance and reduce excessive cooling loads, the thermal behavior of this type of building requires careful investigation. As an increasing interest in double-skin facades as a successful methodology for controlling building performance continues to be explored in Europe , its feasibility within Hawai`i's climate has yet to be discovered. In this study, double-skin façade design strategies are examined in Hawai`i's climate focusing on enhancing thermal performance on an existing building model. This research adopts a CFD simulation approach to model heat and air flow transfers in various double-skin façade design scenarios. The impact of solar radiation, surface temperature, cavity height and air flow rate on temperature and velocity fields inside the channel of the double-skin facade is analyzed. This research focuses on the investigation of context based design for double-skin facades, particularly focusing on design considerations during the design process. In conclusion, this investigation will help to identify the potential of this specific system within Hawai`i's climate and its ability to improve thermal performance within existing buildings.

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I. INTRODUCTION

1. BACKGROUND

It is important to recognize that buildings are one of the major sources of global energy demands; therefore, they have a huge opportunity to avoid significant environmental collapse. According to the U.S. Energy Information Administration (EIA), the Building Sector consumes about half (49%) of all energy produced in the United States and a total of 77% of all the electricity used by buildings in the U.S. is used to operate them.[1] Within commercial buildings, both electrical and mechanical systems account for 30-40% of a building's energy demand and ultimately add to the building's life cycle cost, energy demand and maintenance. The façade of a building represents 15-40% of the capital cost of the building and is the main contributor to the operational cost of the building environmental service systems.[2] With excessive amounts of solar gains entering through the highly glazed envelopes of high rise buildings, these complex environmental parameters play a critical role in the thermal performance of the overall building and ultimately lead to increased energy loads. In order to optimize thermal performance and reduce cooling loads, the thermal behavior of this type of building requires careful investigation. According to an article in the ASHRAE Journal, approximately 86% of building construction expenses relates to renovation of existing buildings and it is estimated that over the next 30 years, about half of the entire building stock in the U.S. will need to be renovated.[3] This movement has been encouraged by political leaders like President Obama who on February 3, 2011 established the "Better Building Initiative" which provides $40 billion in incentives in an attempt to make commercial buildings 20% more energy efficient over 10 years.[4] With an increasing demand in retrofitting and reusing buildings rather than constructing new ones, retrofitting the existing building stock presents the largest potential and greatest opportunity

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[1] Architecture 2030. "Why?" Accessed February 24, 2010. http://architecture2030.org/the_problem/buildings_problem_why
[2] Wigginton, Michael, and Harris, Jude. Intelligent Skins. (Italy: Elsevier, 2002), 3.
[3] Adaptive Building Initiative. "Why Adaptivity" Accessed February 7, 2011.
[4] The White House. "President Obama's Plan to Win the Future by Making American Businesses More Energy Efficient through the "Better Buildings Initiative." Accessed April 27, 2011. http://www.whitehouse.gov/the-press-office/2011/02/03/president-obama-s-plan-win-future-making-american-businesses-more-energy

for the incorporation of energy efficient measures. By understanding the quantitative basis of energy demand in buildings and the impact of its use, we can begin to implement necessary design solutions.

The main concern for commercial buildings today is the relation between energy consumption and thermal stability within the building. With an increase in the demand for highly glazed facades in high-rise commercial buildings, thermal comfort during the summer months creates a major burden on energy consumption. The increasing use of glass facades allows for greater amounts of solar energy to enter the building and have caused internal environments to rely on HVAC systems to offset thermal differentials. Also, with the greater use of IT equipment and electronics, a higher internal heat load is also evident. As the cooling energy demand within these buildings increase, the push for optimizing a buildings thermal performance becomes a necessity.

Recent developments in façade technology are following two trends, one towards nanotechnology where focus is on the development of thin films and coatings that improve façade performance on a micro-level, and one towards large scale double-skin facades aimed at improving the macro-level performance. Regardless of the façade type, the functional performance goals are similar; blocking adverse external environmental effects while maintaining internal comfort conditions with minimum energy consumption. Consequently, the concept of the 'intelligent skin' has begun to take shape within the past few decades. It is a relatively new theory of design that introduces the notions concerning adaptability and responsiveness made possible by technological innovations. As a result, architects, engineers and contractors are able to understand and design building facades systems to improve internal environmental conditions on a much finer scale. The implementation of double-skin facades represents the introduction of intelligence into building design principles as it has the potential to regulate building performance by creating a transition zone between the internal and external environment. The idea of self-adjustment and responsiveness through these systems is made possible by these developments in technology and thus places greater architectural significance with the appropriate application of 'intelligent features'. "Intelligent design means striving to have our buildings in harmony (and integrate) with nature, to protect its qualities, and to recognize its dynamic (and unpredictable) qualities, whether assets or liabilities."[5] David Orr, in his book, "*Design on the Edge"* instills a sense of harmony that is required between man and nature as it is crucial to our well-being. A notion that we should not try to dominate nature as we have in the past, but rather to look at our relationship with nature as more of a symbiotic partnership. It is evident today that this has now become a driving factor for sustainable design around the world.

As an essential performance component of a building, the building's envelope acts as the skin of the building. As compared to human skin, it highlights the intrinsic and integrated quality of the whole building fabric. Rather than a veneer characteristic that is often found in commercial high-rise buildings, a building skin operates as part of a holistic building component, a threshold between the building's internal and external environment. An 'environmental skin' relates to its ability to govern the external, contextual environment in order to optimize building performance. Thus it can be defined as an active and responsive controller of the interchange that occurs between the external and internal environment with a dynamic ability to provide optimal internal conditions with components within its own assembly. A buildings envelope serves as the main layer through which the interior meets the exterior environment, and is therefore the single greatest potential controller of the buildings internal environment in relation to temperature, lighting, ventilation and air quality. As a result, the external skin of a building should not be static, but rather have the ability to optimize conditions in order to provide the ideal response to external climactic conditions. It is an element which performs functions that can independently effect the internal environmental variations to maintain user comfort. With the application of a double-skin facade, the adaptability of a buildings envelope through self-regulated adjustments can assure optimal configuration in relation to thermal performance and allow for greater energy savings by reducing HVAC demand.

Research by the Lawrence Berkeley National Laboratory (LBNL) at the University of California Berkeley on High-Performance Commercial Building Facades identifies the role of facades and the functions they should provide:[6]

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[5] Wigginton, Michael, and Harris, Jude. Intelligent Skins. (Italy: Elsevier, 2002), 25.
[6] LBNL: High-Performance Commercial Building Facades "What is HBPF" Accessed February 18, 2010http://gaia.lbl.gov/hpbf/whatis.htm

- Enhanced sun protection and cooling load control while improving thermal comfort and providing most of the light needed with daylighting;
- Enhanced air quality and reduced cooling loads using natural ventilation schemes employing the façade as an active air control element;
- Reduced operating costs by minimizing lighting, cooling and heating energy use through optimizing the daylighting-thermal tradeoffs;
- Improved indoor environments leading to enhanced occupant health, comfort and performance.

A variety of performative functions must be utilized in order to produce a high-performance design solution. Basic concepts of daylight, ventilation, solar heat gain control, and space conditioning can be combined to create an innovative façade; one which has the ability to achieve a very high level of thermal performance.

This view of high-performance facades creates a dynamic solution which provides a situation where importance is placed on potential benefits from existing environmental conditions. Attention is placed on the functions performed by the building envelope and challenges the passive design approach which has become a leading feature in environmental design. This passive approach may not have the ability to solve all the problems of climate control and, therefore, has led to the need for building facades to become more dynamic and active in response to their environmental context.

An increasing interest in double-skin facades as an intelligent, active responsive system, focusing on fundamental strategies to optimize thermal performance continues to be explored by many designers around the world. The double-skin façade has been used due to its ability to adapt to climatic conditions and take into account local characteristics such as temperature and solar radiation in order to minimize building loads and energy consumption. The aim of this research is to reflect on strategies for double-skin facades that are beneficial to Hawai`i's climate. There are several key parameters that influence design and performance, but building location and climate should be the prevailing considerations. Because both climate and occupancy needs are dynamic, a building's facade must be flexible, having the ability to adapt and respond to variations in the environment and to changing occupancy needs. As a result, the buildings envelope must consider the constraints and opportunities of solar orientation, location, climate, and macro and micro environmental condition. In this study, double-skin façade design strategies are investigated for Hawai`i's climate focusing on retrofitting the First Hawai`ian Center in downtown Honolulu. Building performance is investigated by modeling the energy performance of different design scenarios. In conclusion, this investigation will help to identify the potential of this specific system within Hawai`i's climate and its ability to improve performance within existing buildings.

Today, the concept of an environmental skin can now be centered on an entirely new understanding. The double-skin facade utilizes control systems to allow for the function of the building to become dynamic in relation to its needs. Through the utilization of double-skin façade systems, the need for mechanical and electrical environmental systems can be reduced or even eliminated. Buildings of the twenty-first century must provide variability within the buildings envelope; implementing building facades that will provide a viable position in contributing to the development of low energy buildings, added intelligence in building design, and providing new morphologies for building envelopes. The need to deliver an enhanced building performance regardless of the external climate through the use of innovative systems is vital in our efforts to become a more sustainable society. This new era of highly intelligent environmental facades showcases an evolution in architectural design.

2. PROJECT STATEMENT

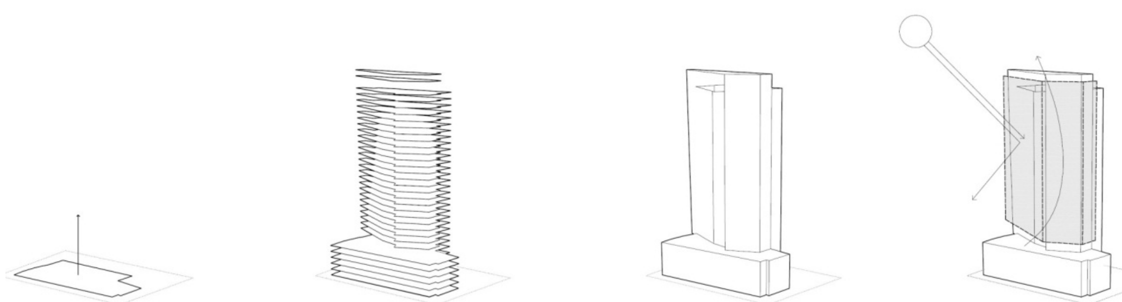
Thermal performance within buildings has become a greater concern for designers in relation to energy consumption. Increasingly greater amounts of solar radiation are now entering buildings through their highly glazed envelopes which cause thermal discomfort for its occupants and increased cooling loads. With concerns focusing on solar exposure, a buildings external heat gain is determined greatly by its orientation, proportion of exposed surfaces and its use of solar shading devices. Other factors which lead to an added internal heat such as computers, electronics and lighting also contribute to an unstable internal environment. As a result, optimizing thermal performance within commercial high-rise buildings in Hawai`i's climates must be addressed. With the increase in cooling demand of these buildings and the need for energy savings, attention must be placed on building operations highlighting the potential for optimizing the behavior of building facades.

In advanced architecture design, the idea of "building surface" and "building skin" as a multilayered aspect of façade design is becoming progressively more examined. Most existing building envelopes are very static and provide very little or no interaction with the environment; serving mainly to separate the interior and exterior environments. With the use of intelligent environmental skins, one has the power to provide the means of cooperation between the two. Through the exploration of double-skin façades, designers are capable of transforming the existing building stock and initiate an improved relationship between the building, its users, and the natural environment. Based on this idea that double-skin facades can be perceived as a façade improving element, a new comprehensive approach can be defined in which building performance is a guiding principle. With the application of double-skin facades, one can design environments that not only engage with its surrounding environment but enhance building performance and user experience.

Within Hawai`i's climate, the feasibility of double-skin facades as a successful system for controlling building performance is unknown. Research has shown that they have the potential to create a regulating element between the internal and external environments which can help to reduce unnecessary cooling loads. In this study, double-skin façade design strategies are investigated to enhance building envelope performance by modeling energy performance of different design scenarios on an existing building model.

The First Hawai`ian Center in downtown Honolulu will serve as the base case upon which the application will be explored. The selected scenarios will be designed and scrutinized by its thermal performance and compared against the performance of the existing fenestration of the building. Since the design of these systems is quite complex when it comes to various considerations, this research focuses specifically on the temperature behavior and air flow characteristics within the selected design model. These two parameters and the geometry of the façade help to define the function of the façade and will provide a basis in understanding how this system may be viable within the overall building. Only then will the use of double-skin façade systems be considered for its potential to become an interactive building element which focuses on fundamental strategies to increase occupancy comfort specific to Hawai`i's climate.

The investigation of this building skin aims to define specific performance strategies as well as represent the ability for future building façade retrofits to further enhance its impact as a climate moderator within the existing building stock. By better understanding building envelopes and their ability to respond to changing environmental conditions to optimize a buildings thermal performance, future design developments can encourage energy efficient opportunities that have the ability to benefit from existing environmental conditions as well as highlight the importance of sustainability.



3. SCOPE & LIMITS

The research and analysis of this project will be accomplished through several methods. A brief discussion on intelligent design, the intelligent facade and responsive environments will help in determining how this architectural movement has gained ground within the past decade. The project will also examine the growing interest of intelligent environmental skins focusing on systems that can be implemented within a building's façade in order to optimize thermal performance. Current comfort standards and comfort factors as parameters for design will be assessed in order to provide an understanding of the impact that the façade has on thermal performance. Research will also include a compilation of various intelligent features that have been found to represent the components within intelligent buildings; what is being called the "genetic characteristics" of the façade of the future. Additionally, these intelligent features will be evaluated with particular relevance relating to its use within double-skin facades. An understanding of the double-skin façade system is described providing information concerning performance issues, construction types and advantages and disadvantages related to its use. Case studies provide references for built examples and help to identify the various features and strategies implemented within current building envelopes. They will also provide a reference to specific simulation scenarios that will be evaluated as to the level of impact they have in enhancing the existing buildings thermal performance. With an understanding of current systems used within buildings today, these systems can be applied to the development of the project investigation. Finally, identifying specific characteristics of the existing building stock in terms of energy usage and typologies will make it possible to determine the potential future application of this project.

This research serves as a foundation for the development of the proposed project. In this study, double-skin façade design strategies are investigated to enhance building envelope performance by modeling energy performance of different design scenarios on the existing building model. Finally a discussion and conclusion section follows in which the point of view of the author is given and comments are made. The research will discuss the potential benefits of double-skin facades as well as list fields of additional research and development needed to further validate double-skin facades within this specific climate.

Due to the complex nature of double-skin facades, this research will be limited to the test of temperature behavior and air flow characteristics within specific design scenarios. This investigation will focus on two major elements that affect the thermal performance of the double-skin façade; energy flow paths and air flow paths. Static variables for all double-skin scenarios have been established in relation to specific constraints of the project as well as information drawn from previous research. These conditions help to select the appropriate boundary condition as well as define and identify what needs to be modeled.

Various modeling and simulation tools exist on both levels; however, DesignBuilder and Ecotect have been used within this specific situation. It has been found that these modeling and simulation tools exist on both levels of analysis but will only provide a specific level of detail. Thus, the limitations of the simulation and network model can only be overcome through a more advanced CFD modeling tool. As a result, the main outcome of the CFD analysis is an improved understanding of the systems; it does not give unique and definite guarantees of the outcome of the analysis and thus there is a need to validate the results. Simulation of the model helps to represent real physical occurrences and simplification of reality into the modeled façade conditions.

4. ORGANIZATION

The main purpose of this research is to give an overview of current developments and investigations related to the topic of 'Environmental Skins'. Focus is placed on double-skin facades on commercial high-rise buildings within Hawai`i's climate and its ability to enhance a buildings thermal performance. Often it is important to describe the current advancements within every aspect yet specific attention has been placed on the double-skin facade and its ability to provide the various levels of thermal performance. This allows for an opportunity to develop and construct a basic structure of this research which focuses on thermal optimization through the implementation of various double-skin building envelopes.

The research will also establish the current level of knowledge and technology, stage of development based on literature, case studies, presentations, etc. The first step is to clearly identify the research approach and to define the framework of interest. In this case, existing literature is used as necessary background knowledge in order to develop an understanding of the current state of intelligent environmental skins as it relates to the development of double walled envelopes. By presenting examples that establish a successful application, one can begin to compare and analyze the various applications within a specific context. Through this investigation the potential benefits of further exploration of these systems within Hawai`i's contextual climate will be stated.

The following sections provide an overview of the following research:

I. Introduction

Project statement, project goals, and methodology implemented.

II. Project Research

1. *A New Era of Innovation*
   Background information on the notion of intelligent buildings, responsive environments, and their effect on the façade.

2. *Thermal Performance & the Façade*
   Thermal comfort, comfort standards, environmental conditioning and thermal comfort factors as parameters for design.

3. *Intelligent Features*
   Established features that construct an intelligent environmental façade and how it relates to overall building performance.

4. *The Double-skin Facade*
   Exploration into the definition and parameters that make up this specific façade type with specific case studies that implement various design scenarios.

5. *Building Stock*
   Development of the high-rise, energy consumption and their specific characteristics; Importance of retrofitting the existing building stock.

III. Project Investigation

1. *Building & Environment*

Setting up the base case model (FHC) and the climate as an environmental context.

2. *Form & Envelope*

Facade model and the study of thermal energy, solar exposure, ventilation on the base case model.

3. *Façade Investigation*

Generating design scenarios, approach and the simulation of the design application and comparative analysis.

IV. Conclusion

Findings/Lesson learned; final comments relating to potential benefits and failures of the specific system as well as possible further research needed for validation.

II. PROJECT RESEARCH

1. A NEW ERA OF INNOVATION

The concept of the 'intelligent building' has begun to take shape within the past few decades; a new era of design which introduces the notions concerning adaptability and responsiveness has been made possible by technological advancements in building design. Designers are now able to understand buildings and their systems on a much larger scale. The use of 'smart materials' represents the introduction of intelligence into building design principles and greater architectural significance can thus be achieved with the appropriate application of these types of intelligent features. This new era of innovation in the field of architecture has led to the design of 'adaptive' and 'intelligent' buildings, buildings that can adjust their performance in response to real time environmental changes.

It is recognized that buildings have traditionally been conceived as places of shelter to protect us from the natural elements of wind, water and the sun. This has led to the idea that we must design and construct buildings to minimize the impact of or defend us from the natural environment. This typical model has proven very rigid, static, and ultimately unresponsive and unsustainable. These ideas of architecture and the built environment center on domination rather than establishing a partnership with nature. A lack of correspondence with the environment has led to an often inefficient or counteracting design solution; an inflexible system designed as a one-size fits all solution. With the lack of design solutions that have the ability to effectively respond to changes in our natural environment, architects and designers alike are aiming towards building adaptations as the means by which buildings can help to address these concerns. "Adaptation is essential for survival and success: This is true for our buildings as it is for all other aspects of life."[7]

A new era of sustainable buildings has come to reality where current technological advances allow for dynamic, intelligent systems to have a greater impact on buildings than those systems operating independently. "It's where the individuals who occupy those buildings have a relationship with the environment around them; where parts of the building think, move, react,

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[7] Adaptive Building Initiative. "Why Adaptivity" Accessed February 7, 2011.

and adapt to real time conditions."[8] What if you could design a building that had the ability to self-adjust itself in order to optimize the environmental conditions within? These possibilities are now becoming realized as a handful of designers are now creating what has been coined a 'living building'.

1.1. Intelligent Buildings

A look at architectural history reveals that designers have relied on innovations in building technology for centuries. Concrete, glass, elevators, HVAC, and artificial lighting have all had a major impact on the evolution of architecture. Today we are able to explore the use of new and innovative materials, systems, and components that lead to a new type of architecture; the creation of intelligent environmental buildings.

Today's intelligent buildings are forerunners of a new wave of architecture. The Intelligent Building Institute defines an intelligent building as "one which integrates various systems to effectively manage resources in a coordinated mode to maximize: occupant performance; investment and operating cost savings; and, flexibility." Modern technologies that enhance the performance capacity of intelligent buildings help to provide an introduction of advanced systems, expanding the capabilities of our built environment:

- Sensing human presence and/or occupancy characteristics in any part of a building and controlling the lighting, heating, ventilation, and air-conditioning
- Systems based on appropriate pre-programmed responses;
- Performing self-diagnostics of all building system components, whether they are exposed or concealed;
- Sensing the intensity and angle of light and solar radiation, temperature and humidity, and adjusting the building's envelope according to desired interior performance levels.

[8] Adaptive Building Initiative. "Why Adaptivity" Accessed February 7, 2011.

In Brian Atkins book, "*Intelligent Buildings*", he begins to describe three main characteristics that an intelligent building should possess:[9]

- *Buildings should 'know' what is happening inside and immediately outside.*
- *Buildings should 'decide' the most effective way of providing a convenient, comfortable, and productive environment for the occupants.*
- *Buildings should 'respond' quickly to occupants requests.*

1.2. Responsive Environments

Responsive environments demonstrate how a set of systems can respond to environmental inputs as a means of producing a given reaction. The interpretation of this interaction is not linear, but rather a multi-loop interactive system which depends on openness and continuous cycles of interaction. At its root, actively responsive design identifies the transaction and distribution of information between two systems (i.e. between a building, its occupants and the environment). The ability to not only monitor, but correspond with environments is an important application of environmental design. Thus, there has been an understanding that intelligent and responsive architecture can arise from an understanding of what it means for objects to interact within nature.

Responsive environments are those in which external conditions are measured (via sensors) and enable an object to appropriately adapt its form, shape and character (via actuators). These actively responsive environments aim to refine and extend the existing environment by improving environmental conditions with the application of responsive technologies (sensors, control systems, actuators) while also producing a higher level of energy performance within buildings. Responsive architecture distinguishes itself from other forms of interactive design as it incorporates intelligence and adaptive technology as the core elements of the building's design.

The most common definition of responsive architecture is its ability to alter its form to reflect the environmental conditions that surround it. The term "responsive architecture" was

[9] Atkin, Brian. Intelligent Buildings: Applications of IT and Building Automation to High Technology Construction Projects, Kogan Page, 1988.

first coined by Nicholas Negroponte in the late sixties when spatial design problems were being explored by applying cybernetics to architecture. Negroponte suggested that responsive architecture is the product of an integration of computational control into built spaces which resulted in a better performing, more rational building: “…it would not only be able to monitor and regulate environmental conditions but also mediate the activity patterns”.[10] This suggests that a responsive environment should have the ability to understand environmental patterns and be able to respond to contextual variations, adding a layer of intelligence into the building that encourages interaction between environmental sensors and controllers which produces responses triggered by contextual conditions.

Tristan d’Estrée Sterk, from the *Office for Robotic Architectural Media Bureau for Responsive Architecture* (OAMBA), has taken this concept of responsive architecture one step further within his recent works. He claims that responsive architecture, the next architectural state of buildings, is determined by the idea to “treat the needs and wants of users as a set of ever changing conditions”.[11] His hybridized model of control for responsive architecture consists of three different functional components; 1) the needs and wants of building users, 2) a building structure with a responsive capability and, 3) a configuration of spaces that are serviced. This outlines a given structure and provides a basis for which new models of responsive architecture may be proposed to produce a responsive quality that relates user needs to actual responsive building components. As seen in Figure 1.1, two types of communication between the responsive structure and space are identified (i.e. a request and a response) whereas the interaction between the structure and the space has been given the name “resulting architecture”. Together, all of these elements combine to produce a form of architecture constantly manipulated by the changing sets of interactions and responding components. The connections between these elements reflect the needs and wants of the defined condition.

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[10] Negroponte, Nicholas. Soft Architecture Machines. Cambridge, London: The MIT Press, 1975.
[11] d'Estrée Sterk, Tristan. “Building Upon Negroponte: A Hybridized Model Of Control Suitable For Responsive Architecture.” The School of the Art Institute of Chicago, 2003.

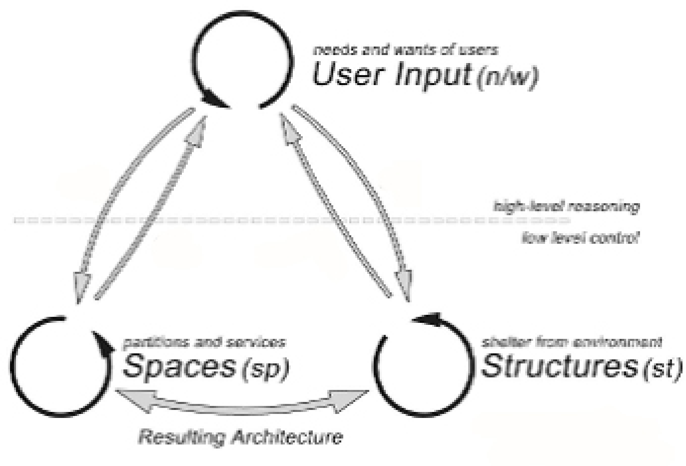

Fig. 1.1: Sterks proposed hybridized control model for use within a functional responsive architecture.

1.3. Intelligent Environmental Skin

A basic function of a buildings envelope, other than encasing the building, is to preserve a comfortable climactic interior environment, protecting the building from the harsh realities of external conditions (i.e. cold, hot, wind, rain). Much like a human skin does a body; a building's skin represents the component which performs the function of protecting the internal environment from the exterior environment. Because this element serves as the main layer from which the interior environment meets the exterior environment, its serves as the single greatest potential controller of the building's temperature, lighting, ventilation and air quality. An 'intelligent environmental skin' acts as to create a performance value; the ability to optimize internal environment regulating the performance of a building. An 'intelligent skin' is recognized as a crucial element which makes up the building as a whole.

If this external fabric of the building is responsive, it can have the ability to preserve a comfortable interior environment as well as reduce external gains of the building and reduce HVAC demand. As a result, an intelligent environmental skin can thus be an active controller, regulating the exchange between the internal and external environment with the capability of serving user needs by optimizing thermal performance.

As an active responsive element, the double-skin facades can provides a context in which an increased importance is placed on performance within our environments. Focus is placed on the interactive controllable functions performed by the building and its envelope, and challenges the passive design approach which has become a leading feature in environmental design and may not have the ability to solve all the problems of climate control.

The requirements within the design of the façade suggest that buildings and their envelopes should be symbiotic, allowing them to work in harmony with one another rather than seen as a secondary treatment, unsupportive and detached from the structure as completely separate entities. With respect to system optimization, double-skin facades can allow for a relationship which enhances thermal performance, natural lighting, and natural ventilation while reducing radiation. This solution must work as an integrated system; one which has the ability to optimize these requirements and allow for a more positive behavior of the building's façade. This would include an intelligent environmental system allowing for a wide range of variations in relation to an ideal configuration. Recent developments in double-skins as an integrated, active system have shown the potential to make buildings of the future into systems that improve a buildings thermal performance and reduce energy demands.

Intelligent environmental systems provide a class of architecture with the means of catering to contextual conditions (i.e. environmental and user). Double-skin facades treat the needs and wants of users as a set of ever changing conditions in constant communication with the environment, the building and its users. Major developments in building envelope design focus on intelligent environments that have the ability to gather and interpret information in order to physically adapt to given constraints. These facade components, with the ability to reconfigure in response to the given external environment begin to address the ever changing individual and environmental needs within our buildings.

Double-skin facades designed to integrate emerging technologies will have a natural intelligence and be able to provide contextual conditions and individual needs. Intelligent facades currently can:

- Be centrally controlled while still providing the occupant with the ability to manually override the system.
- Change their physical properties such as thermal resistance, transmittance, permeability, etc.
- Modify their interior and exterior color and/or texture; function as communicating media facades with video and voice capabilities.

- Change optical properties and allow the creation of patterned glazing providing the opportunity for dynamic shading and remote light control.
- Energy harvesting; deriving energy from external sources (i.e. solar, thermal, wind).

The development of the intelligent and active responsive facade imposes the redefinition of the building envelope. Central controls for intelligent facades will respond to climatic conditions by transforming the building envelope to optimize heating and cooling loads, daylight utilization, natural ventilation, etc. Intelligent facades will allow daylight to penetrate deep into a building's interior and allow the occupant to determine the degree of luminous and thermal comfort along with the degree of visual and acoustical privacy provided by the enclosure. As a result, one can now imagine how active responsive building facades can transform the quality of their environment whenever and however they choose.

2. THERMAL PERFORMANCE & THE FACADE

The fundamental role of buildings is to protect its occupants from external climactic conditions (i.e. extreme temperatures, solar radiation, wind, rain). In construction, the building's facade is the primary system through which external conditions can be influenced and controlled to meet the comfort requirements of the occupants within the building. The need for the 'Intelligent Environmental Skin' begins with this initial demand for enhanced thermal performance. Conventional buildings have often satisfied their performance need with the operation of highly mechanized systems which often require excessive amounts of energy. Buildings representative of conventional design, in which mechanical systems provide 100% of the space conditioning requirements, have become increasingly scrutinized as a result of the growing awareness of creating environmentally sustainable buildings. In air-conditioned buildings, thermal conditions are generally predictable and controllable, with the objective of maintaining consistent indoor thermal conditions uniformly throughout the day, regardless of the exterior climate. Nonetheless, this results in an enormous cost in terms of energy consumption and associated environmental consequences. Developing an appropriate building envelope is an important part of enhancing a buildings overall thermal performance. A well-designed façade can ensure that occupants of buildings have productive and healthy internal environments that do not require large amounts of energy. As a result, high performance building facades must be designed in response to their local context and work with external and internal conditions to achieve optimum conditions within and around the building.

In order to design a successful high performance building, designers need to understand the basic fundamentals of thermal performance. When considering how heat will transfer into the building, one should focus on the use of materials and its ability to transfer/resist heat. The ability for a material to transfer heat is quantified as its U-value and the ability to resist heat transfer is the R-value, both measured in Btus per square foot of area per hour (Btu/ft^2/hr).[12]

[12] Hawaii DBEDT Energy, Resources & Technology Division. *Field Guide for Energy Performance, Comfort, and Value in Hawaii Homes*, (Honolulu; 2002) 20.

These values must be considered when identifying and measuring the amount of heat transfer into the building through its external envelope when specifying material selection.

It is important to note that heat can transfer into a building in a variety of ways (i.e. radiation, convection, and conduction). Furthermore, the transfer of heat travels from warmer to cooler entities, thus the greater the temperature difference the faster the heat transfers. High-rise commercial buildings that are constantly cooled by air conditioning create a high level of temperature difference between exterior and interior conditions. Due to this situation, precautions must be taken to block and mitigate unwanted heat from entering the building as it directly relates to energy savings and thermal comfort. Designers need to understand the basics of heat transfer in order to regulate thermal balance and be able to calculate energy efficiencies of the design to determine the potential energy use of the building.

To be able to evaluate thermal comfort, target criteria for the relevant thermal parameters for design must be established, both design and analysis must be implemented to present a successful solution. Therefore, one needs to define the key indoor thermal climactic parameters, quantify their influence on occupants and determine the influence of the building's façade on these parameters. An overview of thermal comfort and comfort standards will help aid the design and provide an understanding of the impact of thermal performance on the design of an environmental double-skin façade. The aspects of thermal comfort are described so that the analysis, design and implementation of the most appropriate design solution can be discovered in the design project as a means of enhancing thermal performance.

2.1. Thermal Comfort

Human thermal comfort is defined by the American Society of Heating, Refrigerating and Air-Condoning Engineers (ASHRAE) as the state of mind that expresses satisfaction with the surrounding environment. There are three main categories that affect comfort: personal, general, and local.

- *Personal*: factors under personal control
  - Insulative clothing (Clo Value)
  - Activity levels (Met Rate)
- *General:* factors produced by the general environment
  - Air temperature
  - Mean radiant temperature
  - Relative humidity
  - Changes in operative temperature
- *Local:* factors produced by the local environment
  - Air movement/velocity
  - Surface temperatures

These comfort factors should not be perceived as independent elements, but as interdependent elements. For example, air temperature that is considered comfortable is dependent on relative humidity, as well as air movement depends on temperature differences. In order to design a successful, thermally comfortable building, designers need to understand the basic fundamentals of thermal comfort.

Ultimately the success of buildings will be in regards to the measurable environmental factors of thermal control. Thus it is necessary to understand how air temperature, surface temperatures, air movement and humidity are related to heat transfer. The basic modes of heat transfer through and into the building are by means of conduction, convection, radiation and evaporation. Conductive heat flow is transferred through direct contact either through a single material or through multiple materials. A material used on the exterior of the building that is highly conductive can result in rapid heat gain or heat loss if it is not thermally protected. Convective heat flow is transferred through a fluid (liquid or gas) by the change in their heat content; warm fluids rise, cooler fluids sink.[13] In many cases, convective heat flow can be implemented in the form of a thermal flue, creating a stack effect of temperature differentials, drawing cool air into the building and exhausting warm air out. Adequate passive/active ventilation strategies can also be implemented to prevent heat accumulation within occupied spaces. Radiation is heat transferred by invisible electromagnetic waves; when the energy of radiation strikes an absorbing material and is converted to heat.[14] Sunlight creates solar radiation that heats up exposed surfaces that re-radiate the heat at different wavelengths. The amount of solar radiation that strikes a surface is known as solar isolation, producing the largest impact on those surfaces perpendicular to the sun's rays. In order to prevent the infiltration of solar radiation into the interior space of the building, the implementation of solar shading devices, radiant barriers, window treatments, and low thermal mass materials should be considered to avoid the storage of unwanted heat.

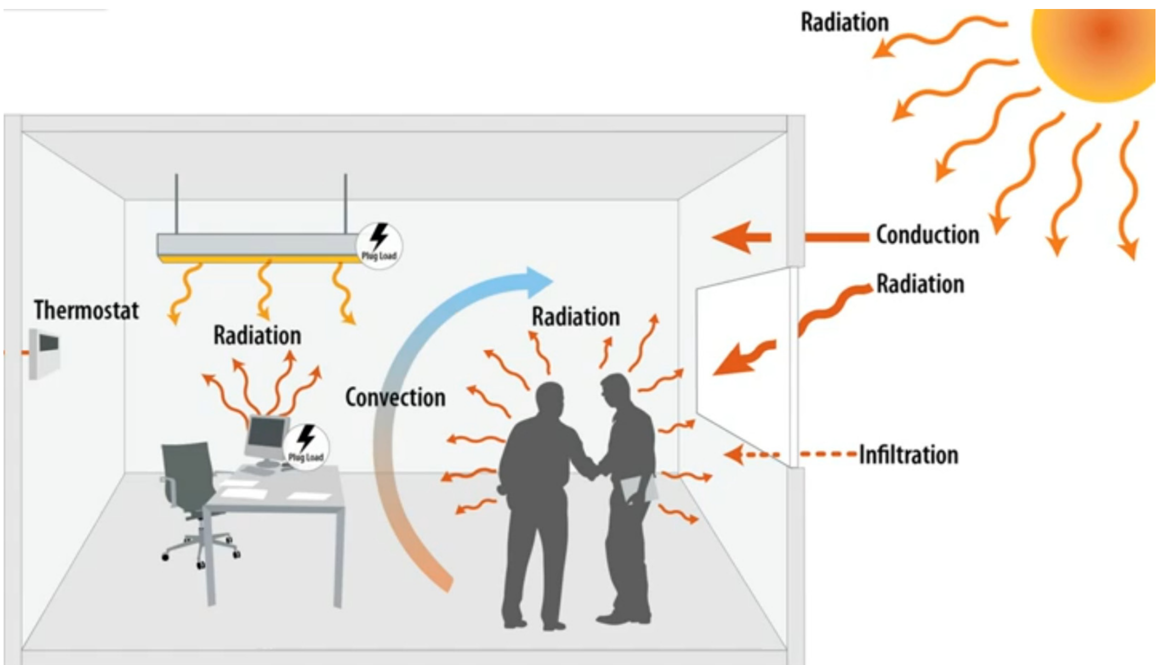

Fig. 2.1: Basic modes of heat transfer through and into the building.

[13] National Institute of Building Science. "Building Envelope Design Guide – Wall Systems | Whole Building Design Guide." Accessed March 2, 2011. http://www.wbdg.org/design/env_wall.php
[14] Hawaii DBEDT Energy, Resources & Technology Division. Field Guide for Energy Performance, Comfort, and Value in Hawaii Homes, (Honolulu; 2002) 21.

Heat transferred by:	*Is Primarily Dependent on:*
Conduction	Surface temperature
Convection	Air temperature, then air motion, then humidity
Radiation	Surface temperature
Evaporation	Humidity, air motion, air temperature

A common experience in buildings is discomfort which can affect the health, performance and the productivity of occupants and has been known to lead to Sick Building Syndrome (SBS) symptoms. A combination of high temperature and high relative humidity in warm and humid climates helps to reduce thermal comfort and indoor air quality and should therefore be addressed. Thus, it is important to control and optimize thermal performance within buildings while also attempting to reduce the energy demand of highly intensive air conditioning systems. With the implementation of 'intelligent environmental skins' one can provide a solution through the use of double-skin building facades that can enhance a buildings thermal performance; implementing thermal and solar control measures to external environmental conditions.

Indoor air temperature:

The comfort zone for indoor air temperatures range from 68-77^{o}F (20-25^{0}C) based on Fanger's Predicted Mean Vote (PMV).[15] With an adaptive comfort approach indoor temperatures in Hawai`i can range from 75-84^{o}F (24-28^{0}C) allowing for a 90% acceptability and 80% acceptability would allow for temperatures to range from 73-86^{o}F (23-30^{0}C). When internal temperature and relative indoor humidity are properly adjusted, optimal indoor air temperature can be achieved. As HVAC systems are the primary method of space cooling, it is important to understand their energy demand when providing comfortable interior environments. Increases

[15] ASHRAE. "ANSI/ASHRAE Standard 55 – Thermal Environmental Conditions for Human Occupancy." Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2010.

in external and internal gains play a large part in increased indoor air temperature and thus an increase in system load.

Radiation:

Radiation penetrates air without heating it, but heats the objects it strikes. A person walking from shade into sunshine will sense a higher temperature, although the air temperature remains the same. According to the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) 55-2010 the radiant temperature asymmetry in the vertical direction should be less than 5 K and in the horizontal direction less than 10 K to limit local discomfort. Whenever possible, these temperatures should differ by no more than 2-3 K from the indoor air temperature; the differential between various surface temperatures in surrounding areas should not exceeded 3-4 K.[16]

Air change and air movement:

A minimal air change rate of 0.3/h is acceptable for unoccupied rooms, the value rises to 1.1/h during hours of operation. This relates to a fresh air intake of 430-650 ft^3/h per person. According to International Standards Organization (ISO) 7730 the mean air velocity should not be less than .8 f/s for moderate thermal environments with light activity during cooling. Air movement at a temperature below 98^{O}F (36^{0}C) cools the body; at the same time it is important to avoid draughts by ensuring that air velocity does not exceed .5 ft/s.[17]

Relative air humidity:

Depending on room temperature, the comfort zone for relative indoor humidity ranges between 30 and 70% with optimal at 50%.[18] High relative humidity, together with high air temperatures, increases heat stress because the body cannot be cooled by evaporation.

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[16] Schittich, Christian, *In Detail: Building Skins*, (Germany: Kosel GmbH & Co. KG, 2006) 31.
[17] Holm, D. & Engelbrecht F.A. "Practical choice of thermal comfort scale and range in naturally ventilated buildings in South Africa." *Journal of the South African Institution of Civil Engineering47.2* (2005): 9-14.
[18] Schittich, Christian, *In Detail: Building Skins*, (Germany: Kosel GmbH & Co. KG, 2006) 31.

All comfort related parameters can be directly controlled and regulated through the design of the building envelope and is the principle guiding factors in the formation of the building skin. The indoor air temperature and average surface temperatures is the product of the exchange between internal and external conditions. Air change and movement can be regulated through a number of ventilation strategies. Luminance and daylighting are also influenced by the composition of the building's façade. As a result, a well-designed envelope is capable of producing a high performance solution with the help of proper design.

2.1.1. Comfort Standards

Basic comfort criteria have been developed by ASHRAE to establish thermal comfort standards and guidelines for interior environmental conditions. One of the goals of their research is to optimize and make consistent ASHRAE Standards to achieve measured and verified high energy efficient systems with high indoor environmental quality.[19] ASHRAE Standard 55 specifically focuses on thermal environmental conditions for human occupancy. Fanger's Predicted Mean Vote (PMV) model forms the basis for ASHRAE standards for thermal comfort that are followed internationally.[20] The results of these uniform comfort standards for all types of buildings and climates were widely criticized around the world as it did not take into account the ability for humans to adapt to the mean temperatures within their climate. As a result, the application of Fanger's PMV model produced oversized systems which lead to over conditioned spaces causing discomfort with a high level of energy consumption. Recognition that the International standard for indoor climate, ISO7730, does not take into account the adaptive principle led to an understanding that thermal comfort is a "complex adaptive system"; a multitude of interacting nonlinear variables.[21] Comfort standards should relate indoor temperatures to the external temperatures as an initial step towards achieving sustainable indoor climates. Thus, it can be used as a useful guide for design as it defines the range of

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[19] ASHRAE. "ASHRAE – Home." Accessed April 8, 2011.
http://www.ashrae.org/

[20] Fanger, P. O., Thermal Comfort, Analysis and Applications in Environmental Engineering, (New York: McGraw-Hill, 1972)

[21] Indraganti, Madhavi. "Adaptive Model of Thermal Comfort." Accessed April 10, 2011.
http://www.scitopics.com/Adaptive_Model_of_Thermal_comfort.html

comfortable conditions for the occupants with the means of adaptability within the climate context.

By recognizing this adaptive model in the thermal comfort standards of buildings, the case for developing a façade that can become a regulating system can be justified. As a result, adaptive comfort standards must be reviewed and used as basic guidelines for design, and specify the internal conditions that must be met. Standard 55, Section 5.3, serves as basic comfort criteria for internal environmental conditions. Based on the various approaches used for space conditioning, specific conditions must be further defined as to address the particular focus of this project in Hawai`i's climate. A review of the adaptive thermal comfort standards follow.

2.1.2. Adaptive Comfort

Studies conducted in hot and humid climates have shown that the International standard for indoor climate, ISO7730 based on Fanger's predicted mean vote (PMV) equation, does not adequately describe comfortable conditions. Fergus Nicol's 2004 study on *Adaptive thermal comfort standards in the hot-humid tropics* presents evidence as to the ways in which International standards are failing and how they might be complemented using adaptive comfort standards derived from local comfort surveys; particularly with the implications of air movement and humidity.[22]

[22] Nicol, Fergus "Adaptive thermal comfort standards in the hot-humid tropics." Energy and Buildings 36 (2004): 628-637

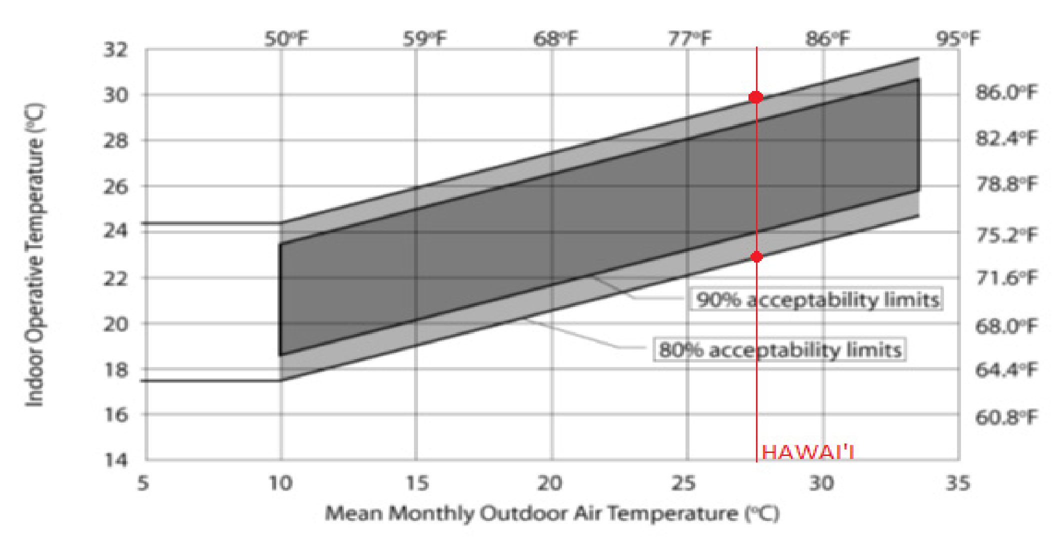

Fig. 2.2: The ASHRAE 2010 adaptive comfort standard (Hawai`i's adjusted indoor operative temperature)

International standards describe comfortable environments based on theoretical analysis of human heat exchange within the environment under supervision of climate-controlled laboratories. ISO 7730 uses Fanger's Predicted Mean Vote (PMV) formula which predicts a numerical value for the mean thermal environment from the six thermal variables; metabolic rate (M), clothing insulation (I_{cl}), air temperature (t_a), radiant temperature (t_r), the water vapor pressure (p_a), and the relative velocity of the air (v_{ar}).[23] Nicol concludes that the resulting formula fails to recognize that people will tend to adapt to the mean temperature within their climate. The PMV predicts that people will feel hotter than they actually are, therefore resulting in the use of more air conditioning then needed.

In 2004 ASHRAE was the first to adopt and incorporate this adaptive comfort concept into a regulator document with an adjusted comfort chart.[24] (Fig. 2.2) The comfort chart specifies optimum indoor temperature as a linear function of mean monthly outdoor temperature. Two acceptable comfort zones extend past the optimum indoor temperature; 90% and 80% acceptability. An indoor temperature falling within the 90% range is expected to

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[23] Nicol, Fergus "Adaptive thermal comfort standards in the hot-humid tropics." Energy and Buildings 36 (2004): 628-637

[24] ASHRAE. "ANSI/ASHRAE Standard 55 – Thermal Environmental Conditions for Human Occupancy." Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2010.

satisfy 90% of occupants where as temperatures within the 80% range is expected to satisfy 80% of occupants. In Hawai`i where the mean monthly outdoor air temperature is around 79^{o}F (26^{0}C), an indoor temperature falling within the 90% acceptability limit would allow for a range of 75–84^{o}F (24-29^{0}C) and a temperature of 73-86^{o}F (23-30^{0}C) within the 80% range.

The Adaptive Comfort criteria have since been adopted in the ASHRAE Standard 55-2010, Section 5.3. A shift in international standards recognizes the benefit of adaptive thermal comfort, the notion that people will tend to adapt to the mean temperature within their climate. As a result of this recognition, the comfort zone can shift upwards in warmer weather climates, specifically where occupants have the ability to manually adjust their environment to restore comfort. The adaptive comfort model is not applicable in buildings where occupants are removed from thermal control of their environment.

2.2. Environmental Conditioning

Growing concerns about energy efficiency, along with the rapid growth of the sustainable architectural movement, has led to renewed interest in how we condition our buildings. All the benefits: thermal comfort over a wider range of temperatures, based on the adaptive comfort zone; reduced energy consumption compared to conventional air-conditioned buildings; and fewer sick building syndrome symptoms, can be realized through the use of an intelligent environmental façade system. However, this interest also is coupled with a variety of concerns and design challenges. Given our modern expectations, the lack of predictability and control over indoor thermal conditions in naturally ventilated buildings cause considerable concerns. As a result, many innovative buildings are exploring mixed-mode systems, which is a way to combine the best features of naturally ventilated and air-conditioned buildings. This section provides an overview of mixed-mode buildings, and describes current applications in relation to providing an adaptive thermal comfort condition.

2.2.1. Mixed Mode Model

A mix mode model utilizes a hybrid approach to space conditioning, combining both natural ventilation and mechanical systems to provide air distribution as a means of cooling the interior. A well-designed mixed mode system allows for the building to be naturally ventilated in times when exterior conditions are desirable, and uses air-conditioning for supplementary cooling when natural ventilation is insufficient. The goal of a mixed mode approach is to ensure acceptable comfort while minimizing significant energy use and operating costs of air conditioning. Mixed mode buildings are often classified by their operation strategies; concurrent (mechanical cooling and natural ventilation can operate in the same space at the same time); changeover (the building switches between mechanical cooling and natural ventilation on a seasonal or daily basis); or zoned (mechanical cooling and natural ventilation operate in different areas of the building). [25] Each chosen approach requires considerable consideration to identify a suitable operation strategy which effectively addresses occupancy needs.

A key to all high performance design is an integrated design approach. In the case for high rise commercial buildings, a zoned mixed mode would result in an integrated approach where highly mechanically conditioned spaces such as server rooms and electrical equipment are clustered and open plan office spaces utilizing the benefits of natural ventilation. The Federal Building in San Francisco by Morphosis provides an example of this approach. This zoned mixed mode building designates the lower five floors as fully sealed and fully air-conditioned, primarily driven by security reasons, but also programmed so that spaces with intensive computer use or other high air-conditioned needs are placed on those floors. The remaining 13 floors are zoned such that the perimeter spaces are all open plans and entirely naturally ventilated, closed offices and conference rooms are located along the central core to allow for air-conditioning.[26]

A naturally ventilated or mixed-mode building likely will be successful only if the building has been intelligently designed to incorporate other climate-responsive strategies as well. Particular attention should be paid to the facade and its ability to reduce cooling loads, as well providing direct ventilated cooling during the day which might be combined with nighttime cooling. Even in an extreme climate, an integrated design solution will extend the times of the year when mechanical cooling can be avoided. The operation of a mixed-mode building requires a paradigm shift from the “centralized control” way of thinking. Ideally, the building should

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[25] Brader, Gail S. “Mixed-Model Cooling.” ASHRAE Journal 48 (2006): 30-37.

[26] McConahey, E., P. Haves, and T. Christ. “The integration of engineering and architecture: a perspective on natural ventilation for the new San Francisco federal building.” Proceedings of ACEEE Summer Study on Energy Efficiency in Buildings. 2002.

allow for natural ventilation as much as possible, and encourage maximum responsive control of the facade to realize the benefits of an adaptive opportunity. When the air conditioning is used, it should be supplemental, a form of control to keep thermal conditions from rising above the adaptive comfort zone.

2.3. Parameters for Design

It is important to note that heat can transfer into the building through a variety of ways. In high-rise commercial buildings that are constantly cooled by air conditioning, a high level of temperature difference between exterior and interior environment is established. Due to this condition, precautions must be taken to block and mitigate unwanted heat from entering the building as this can affect the thermal performance within the building.

All comfort related parameters can be directly controlled and regulated through the design of the façade. The indoor air temperature and average surface temperatures are the result in the exchange between internal and external heat gains. Air change and speeds can be regulated through the use of ventilation openings in the building skin. Close regulation will provide a well-designed building skin that is capable of producing a comfortable internal climate with the help of environmental control strategies even when less than favorable external climate conditions are present.

The performance of the building's skin has constantly been a key concern for internal comfort and conditioning. A building's skin is designed in response to regional climactic conditions, recognizing its significance in relation to occupancy comfort. With an increasing demand for highly glazed facades within high rise commercial buildings, greater concern between energy consumption and thermal stability has become apparent. Cooling energy requirements are increasingly important in the context of office and administration buildings where internal cooling loads are rising. Components that protect from excessive heat gains as well as provide adequate ventilation strategies to minimize extreme internal and external are conclusively important. In conventional office buildings, approximately 40% of total energy consumption is dedicated to the operation of air-conditioned systems for both cooling and ventilation.[27] In order to increase comfort and reduce energy consumption, the cooling demand must be reduced by means of improved building performance through the facade and by executing protection strategies. Additionally, excessive heat gains should be reduced via air exchanges through natural ventilation and careful selection of building materials. Elements that are flexible in both design and use are essential and effect internal comfort requirements. Depending on the specific building requirements, reducing external heat gains or internal ventilation for cooling, these comfort standards can be optimized with an active responsive double-skin façade.

One of the major roles of the building's envelope is to regulate prevailing conditions of the external environment as a means of ensuring comfortable conditions of the interior. Elements such as mechanical systems and external climactic conditions should be understood as supplementary systems that help to support the facade in order to provide internal thermal comfort. Thus, the building's façade must react to climate conditions to regulate how these elements can affect the internal thermal comfort. This direct relationship between a buildings skin and climate control begins to address the basic fundamentals of human thermal comfort. A successful design solution understands the thermal comfort factors as parameters for a successful design solution.

[27] Schittich, Christian, In Detail: Building Skins. (Germany: Kosel GmbH & Co. KG, 2006) 33.

The façade of a building forms the interface between the environment outside and the user inside. It must ensure a comfortable indoor climate and prevent the entry of too much solar radiation. It has to provide daylight deep into the interior during the period of building use and control natural ventilation. The objective in the design of the façade is to find the optimum compromise between the internal and external environment and the requirements of the planned building use.

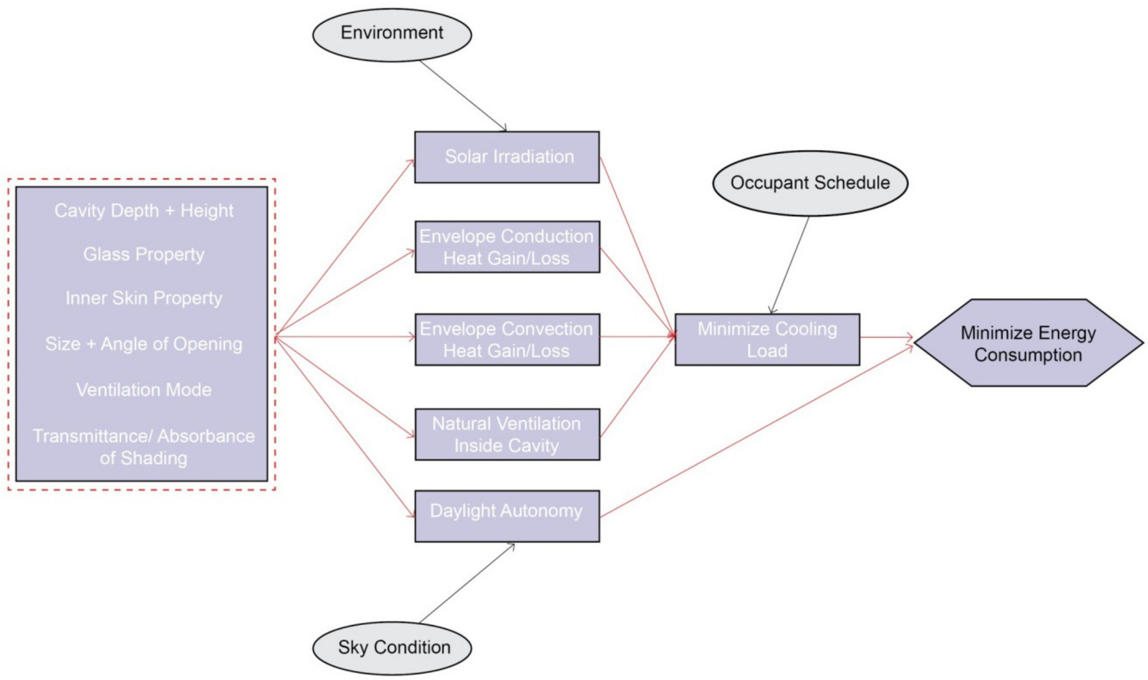

Fig. 2.3: Façade interaction diagram.

3. INTELLIGENT FEATURES

The research of this project has led to the recognition of various 'intelligent features' as identified by the Intelligent Façade Programme in the book *Intelligent Skins* by Michael Wigginton and Jude Harris. These intelligent features have been found to represent the components within built examples of intelligent buildings and what is being called the "genetic characteristics" which establish the makeup of the intelligent environmental skins, "the genes of the intelligent façade of the future".[28] These 'intelligent features' have been identified as the essential components of what generates the justification for building facades to be considered intelligent. The intelligent environmental skin is therefore defined as a composition of genetic elements which combine and overlap to aid in the performance of functions that can essentially respond to environmental conditions through the use of self-adjustment. These 'genetic characteristics' which make up the existing fabric of the intelligent skin are described as the following:[29]

- <u>Building Management Systems (BMS):</u> The 'brain' of an intelligent building, receiving and processing information in order to determine an appropriate response.
- <u>Environmental Data:</u> The ability to collect real time environmental data.
- <u>Solar Controllers:</u> Active systems that respond to solar angles, providing optimum positions for shading and reflection.
- <u>Occupant Control:</u> Maximum personal control over their direct environment, allowing for manual overrides.
- <u>Ventilation Controllers:</u> Automatic regulation of ventilation controlled by operable elements in the building fabric.

These 'genetic characteristics' which consist of the features within an intelligent building skin must be analyzed with a particular relevance to the design project. Although it is important

[28] Wigginton, Michael, and Harris, Jude. Intelligent Skins. (Italy: Elsevier, 2002), 39.
[29] Wigginton, Michael, and Harris, Jude. Intelligent Skins. (Italy: Elsevier, 2002), 39-42.

to understand these systems individually, one must realize that these systems must not act independently. For the scope of this research project, the following sections investigates and critiques each 'intelligent features' and their ability to control a buildings thermal performance. An overview of each feature provides background information on what has been considered the 'genetic characteristics' of an intelligent building.

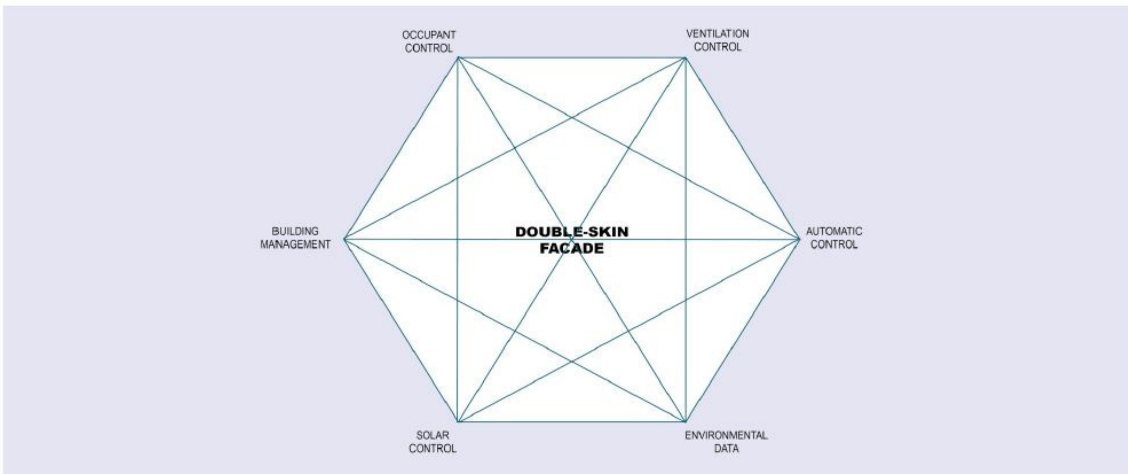

Fig. 3.1: Intelligent features integration diagram.

3.1. Building Management Systems (BMS)

The notion of building intelligence has conventionally been associated with the management and computerized control of building systems. The word intelligence can be very difficult to define; nevertheless, it has recently become a marketing tool for developers, defining "flexible" design solutions for adaptability through the implementation of Information Technology (IT). The acquisition, processing, and storage of this information, based on computation by a central processing unit within a building forms the 'brain' of an intelligent building. This 'brain' is an essential part of an intelligent building, a central processing unit known as the building management system (BMS) is a component that receives various sensory information and determines the appropriate controlled response to the interactive components.[30] An 'intelligent' BMS has the ability to track weather changes in order to control and monitor the operation of both active and passive systems to respond to the desired condition. An intelligent BMS gives the building a degree of artificial intelligent control, anticipating how a building should potentially respond to environmental conditions in order to enhance energy performance and optimize internal comfort for its occupants. This notion of an intelligent building begins to define itself through the use of a BMS allowing for a behavior quality that allows for physical transformation as a need to provide optimal comfort and environmental conditions.

Integrated Building Management Systems (IBMS) are a comprehensive information delivery system that monitors and controls a variety of functions and systems as a means to provide an optimal level of building efficiency. These systems consist of various components that help to manage the controllable elements within the building. A Building Automation System (BAS) is a micro-processor control system designed to monitor and control all functions of the active systems within the building (i.e. HVAC, electrical, fire protection, elevators, and other building services).[31] With the implementation of Building Automation Systems (BAS), the control system is computerized and designed to monitor and control the performance of the systems within the building to aid in the performance of the building with respects to energy conservation. BAS allows for optimization of building performance as it monitors internal and external conditions and controls all energy systems. The BAS has the ability to automatically control the building's façade and all HVAC equipment as well as constantly monitor and track data from environmental sensors including temperature, indoor air quality, ventilation, relative humidity and solar radiation. As a result, the BAS can be optimized to provide the highest level of thermal performance while reducing its energy consumption. A building controlled by a BAS is truly an intelligent building.

The use of BMS is not a new concept when it comes to the management of building systems. It is a complete management system that regulates the variety of systems within the building. As it is an essential component to building management today, the design and

[30] Wigginton, Michael, and Harris, Jude. Intelligent Skins. (Italy: Elsevier, 2002), 39.
[31] "Integrated Building Management Services – Building Automation Systems, Building security systems," Spectral Services, Accessed March 29, 2011. http://www.spectralservices.net/services_ibms.html

implementation of new 'intelligent' systems, components that have the ability of adaptability, will have the capability to be integrated into the intelligent features of the building.

Figure 3.2 displays how an Integrated Building Management System (IBMS) acts as comprehensive information system that monitors and controls a variety of building functions. The IBMS is a central controller which receives the various sensory information as inputs and produces a given response to the various elements. Other control systems implemented within the building services such as the Building Automation System (BAS) and the Energy Management System (EMS) also link with the IBMS. This system of control is not linear, but a multi-loop interactive system which depends on openness and continuous cycles on interaction.

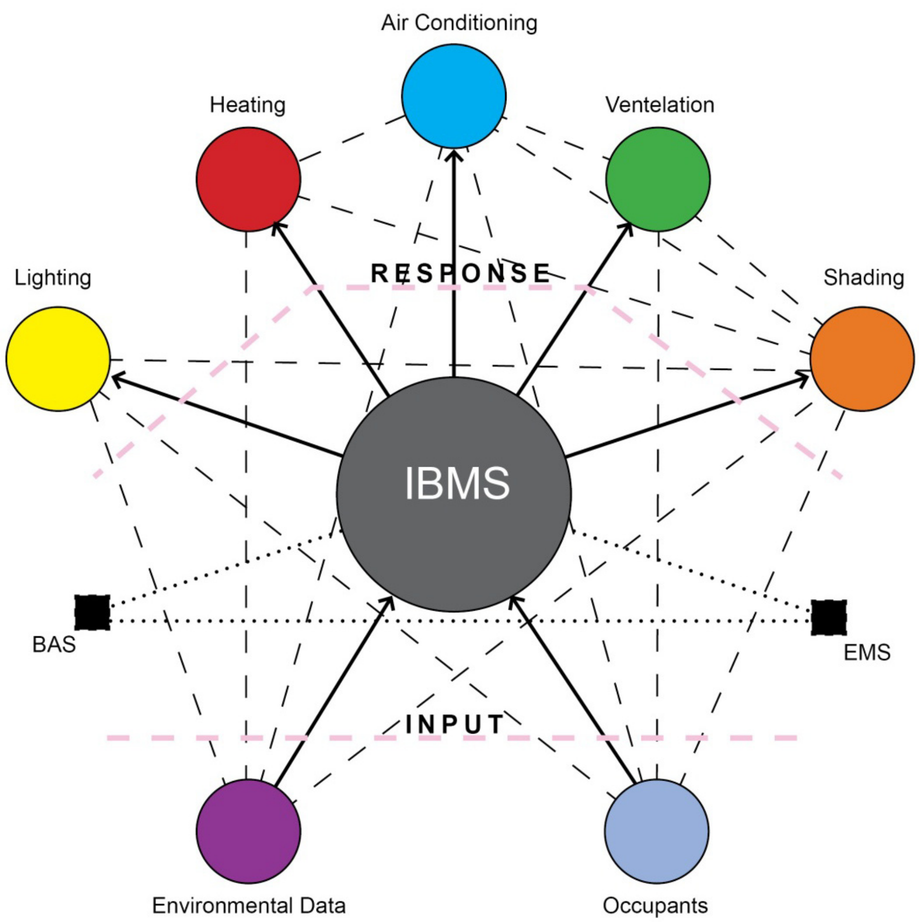

Fig. 3.2: IBMS control diagram.

Benefits of an Integrated Building Management System (IBMS):

Building tenants/occupants

- Control over internal comfort conditions
- Possible individual room control
- Effective monitoring and targeting of energy consumption
- Effective response to lighting, heating, ventilation, shading and air-conditioning systems

Building Owner

- Central or remote control and monitoring of building
- Individual tenant services and facilities management
- Active monitoring of energy consumption
- Improve building reliability

3.2. Environmental Data

Human comfort is affected by air temperature, air flow, radiation and humidity therefore is it important to collect accurate environmental data to improve climate and comfort of internal conditions. In order for a building's façade to respond to local climactic conditions in terms of thermal performance, it is extremely important to collect detailed real-time information relating to conditions inside and outside of the building. This data collected is based on the measurement of the state of the environment and its impacts on the conditions of the building. Typical measurements consist of outside and inside temperatures, temperature of the façade and its cavity, wind speed and direction, inside and outside humidity levels, solar insolation, and daylighting factor. These measurements are monitored with the use of various sensors placed throughout the building and transmit their data through a network to a main location (i.e. BMS, micro-controllers, etc.). For environmental observations, sensors must be considered in the context of the environment in which they are placed in order to allow for accurate gathering of information. As a result, various technological issues need to be addressed to ensure the spatial and temporal level of the environmental sensors. Standards need to be developed to ensure the accuracy of sensors, the network, and the data collection as they relate to microclimatic conditions of the given site. The specific location and measurements are described as such:[32]

Measurement locations:

Measurements in each room:

- Room ambient temperatures (3 heights, 3 distances from façade)
- Façade surface temperatures (3 heights on the different layers of the façade)
- Façade cavity temperatures
- Room ambient humidity
- Transmitted solar radiation through the façade
- Outlet/inlet airflow rate and temperature

Outdoor measurements:

- Total solar irradiance (on vertical)
- Long wave irradiance (on vertical)
- Illuminance (on vertical)
- Dry bulb temperature
- Relative humidity
- Wind speed and direction

The purpose of the measurements can be identified in two different ways. The main objective of the system is to provide real-time measurements in order to accurately control and regulate the change of the different parameters of the façade; the ability to actively reconfigure the control systems as a response to the given environmental data. In addition, the measurements can be used to analyze the existing thermal behavior of the façade, extending the existing system database as it relates to the overall thermal performance of the building as a whole. These measurements can thus be used to understand the annual thermal conditions of the building throughout the seasons and help to provide accurate façade patterns in response.

[32] Poirazis, Harris, “Double-skin Facades for Office Buildings.” (PhD diss., Lund Institute of Technology, 2004.)

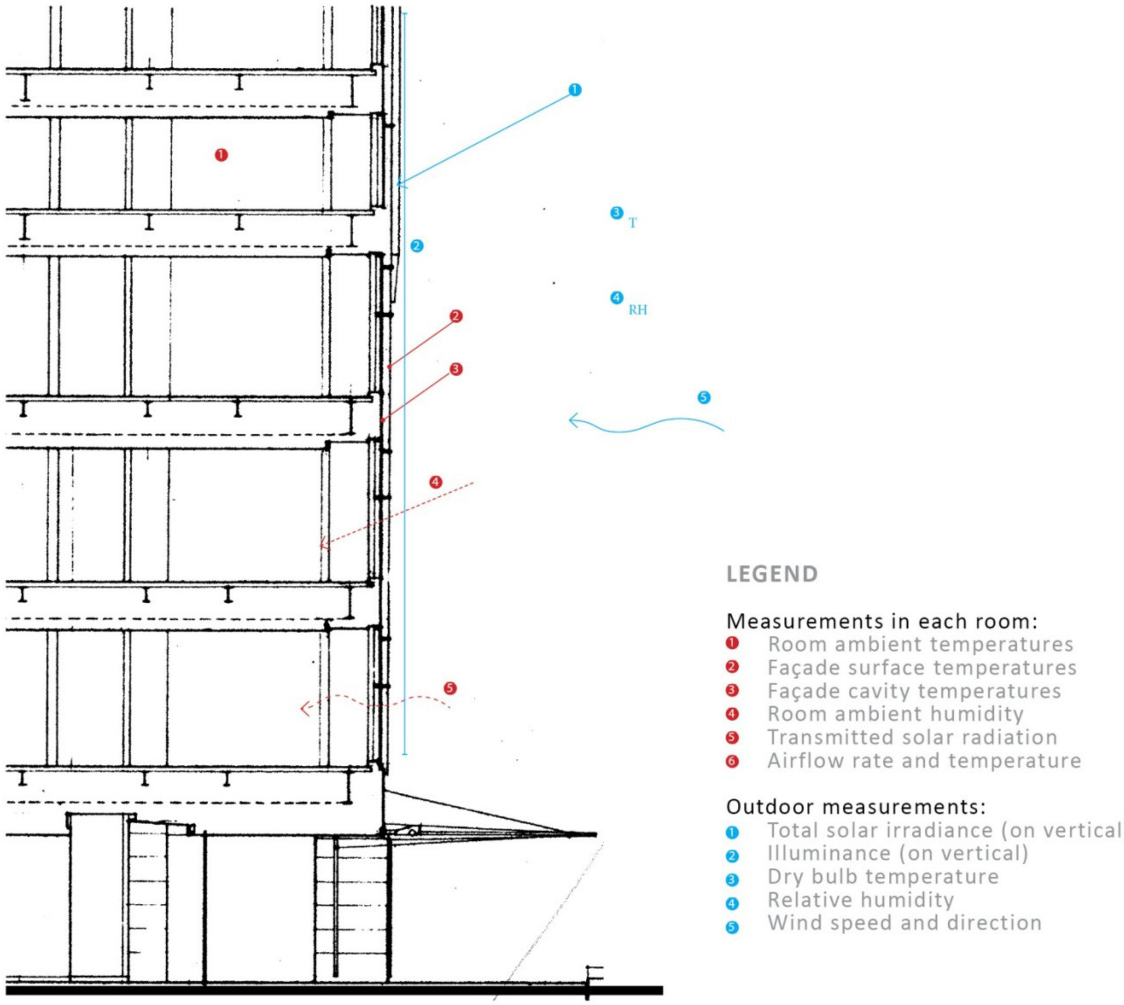

Fig. 3.3: Specific location and type of environmental measurements needed.

Anemometers:

An anemometer is an instrument used to measure wind speed, pressure and direction. By measuring the wind direction and speed of air as it hits the façade of the building, data can be logged and sent to the BMS as real-time information. In terms of natural ventilation, this information is useful as it provides background information on specific site conditions. With the analysis of this data, a building's façade has the ability to interpret this information and actively respond its configuration to suit the needs of the internal conditions; it can actively increase or decrease the flow of natural ventilation into the façade and the internal space to optimize internal thermal comfort. It is important to note that there are several types of anemometers that can be applied both internal and externally, thus it is important to understand what and where you will be taking measurements.

Humidity and Temperature Sensors:

Relative humidity and air temperature sensors must be implemented as a means of monitoring the thermal conditions of the building and its external environment. As these components are essential to the thermal properties of human comfort, constant monitoring is crucial to protect internal thermal comfort standards. Data sensors must be located within the interior environment of the building to identify current indoor conditions and what adjustments should be made to reach a thermal comfort standard. External sensors help to gage exterior conditions and inform the system of the quality of air that will enter the building and whether or not it needs to be conditioned before entering the building. Accurate relative humidity readings require accurate air temperature readings taken at the same location and time. Thus it is important to have an integrated sensor that takes both measurements simultaneously for the best possible precision.

Radiation Sensors:

Radiation data is important in calculating the amount of solar radiation hitting the building's facade by determining the amount of sunlight striking a specific surface. These sensors can be used to measure the electromagnetic radiation from the sun at it pertains to its effect of the buildings envelope. In Hawai`i, unshaded facades are exposed to high levels of solar radiation and therefore it is extremely important to monitor and track heat as well as the heat that is re-radiated into the internal spaces.

Constant records must be logged and evaluated to provide accurate information about the levels of external heat gain of the building's façade and to allow for the controllers to provide an appropriate response as needed. It is extremely important to have accurate environmental data sensors tracking both the macro and micro climactic data of the site. Because thermal comfort relies on various elements, a vast array of sensors must be implemented. Rooms must be constantly monitored in terms of energy consumption and internal environment conditions; room temperatures as well as temperatures across the façade system. The buildings envelope and its configuration is not an independent systems, yet and integration between the façade and environmental systems.

3.3. Automatic Controls

The term controller, when used in computing, means a chip or electronic device that interfaces with an external device.[33] In terms of controlling the building's façade, this may link between the various environmental data sensors and the control of an external device which manages the operational component of the buildings intelligent façade. Specifically with the operation of an environmental skin, various applications and controllers may be implemented throughout the design. Like the BMS the building automation system can act as a central controller, monitoring environmental data input and relaying a specific out put the facades operational devices to perform a specific task. This setup allows the BMS to be the central controller of the intelligent building. In contrast a microcontroller such as the Arduino, is a small computer within a single integrated circuit that has the ability to perform these same tasks, can also be integrated into the system to allow for an even more individualized active response.[34]

These controllers are intended to create interactive objects or environments responding to a specific external stimulus. Controllers work in that way that they can sense the environment by receiving an input from a variety of sensors and in return can respond to its environment by controlling lights, motors and other actuators. With an attention to the specific design and layout of the controllers and microcontrollers, various façade operations can be explored. For example, if the design calls for a very specific micro responsive condition, each active element of the façade can be controlled by a microcontroller. This creates a closed loop or self-contained system, and allows for each individual part of the façade responding according to its micro climactic conditions. In contrast, with the implementation of the BMS as the central controller of the system, all of the components of the façade are linked to a central computer. A hybrid approach can also be considered allowing for each individual unit to respond to its micro

[33] "Controller (computing)," Wikipedia, the free encyclopedia, Accessed April 1, 2011.
http://en.wikipedia.org/wiki/Controller_(computing)
[34] "Arduino – HomePage,"Arduino, Accessed March 23, 2011.
http://www.arduino.cc/

conditions while having the opportunity to be linked back to the BMS to allow for a whole system operation and control. By implementing this hybrid control system, this allows for individualized responsive action while allowing the central controller (the BMS) to override and monitor each individual component of the active responsive façade.

3.4. Occupant Controls

An important feature that must be introduced into the façade is the means for occupant control. Although the system will have the ability to self-adjust itself in response to the existing environment, building occupants should have full control over their immediate environment. Intelligent systems should provide for a manual override to allow for occupancy control as occupants tend to act to restore their comfort if a change occurs that produces discomfort.[35] These controls can be provided by means of manual adjustments or the use of control panels and remote controls. This adds a level of self-adjustment to the system and provides the ability for individual adaptation provided by personal control. In intelligent environmental facades, a mix mode system of occupancy and active control systems must be implemented to allow maximum personal control of the direct internal environment. On the other hand, we must not rely on occupant control as an effective way of achieving optimal levels of thermal comfort. In the situation which unmonitored occupant control compromises the general comfort and energy reduction strategies of the building, the BMS or automation system must either remind the user of its error or have the ability to readjust its configuration to the appropriate condition.[36] With the application of an intelligent environmental façade, the feature of individual occupancy control must be addressed as it provides immediate adaptability for a customizable interior environment.

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[35] Nicolai & Humphreys 1972
[36] Wigginton, Michael, and Harris, Jude. Intelligent Skins. (Italy: Elsevier, 2002) 40.

3.5. Solar Controllers

In order to address the issue of thermal performance, the use of solar controllers must be implemented to either reduce or promote the resource of the sun. In many buildings today, the use of solar control can be seen in the implementation of solar shading devices. Levels of solar control can be explored through the design of façade orientation, specific window conditions, and the use of solar shading devices. These solar control devices can be integrated into the façade system to be modified as it relates to the internal comfort conditions. With the use of solar tacking devices, it makes it easy for the system to determine real-time solar angles as is relates to the sun path in a given day, time and location.[37]

The amount of solar energy entering a building through the façade is determined by the total solar transmittance through the glazing and the shading factor of the solar screening as well as the conductive and radiant control in the glazing materials.[38] (Fig. 3.4)
As a result, the total solar energy entering the building at any given time is relative to the treatment of these elements. Solar shading devices can be located on either the interior or exterior of the building and plays a huge role on its ability to deter unwanted solar heat gain. Exterior shading devices are the most effective method of reducing heat gain in a building through its windows by reducing radiant heat transmittance. Within the case of high rise buildings wind forces can be problematic and should be accounted for within the design of solar shading devices. It is important to design shading devices to adapt to the sun's path and angle as it hits the building's façade. Installing shading devices within a double-skin façade cavity can be highly efficient, allowing ventilation to wick off any built up radiant heat.

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[37] Wigginton, Michael, and Harris, Jude. Intelligent Skins. (Italy: Elsevier, 2002) 40.
[38] Hausladen, Gerhard., de Saldanha, Michael., and Liedl, Petra. ClimateSkins: Building-skin Concepts that Can Do More with Less Energy. (Berlin: Birkhauser, 2008) 46.

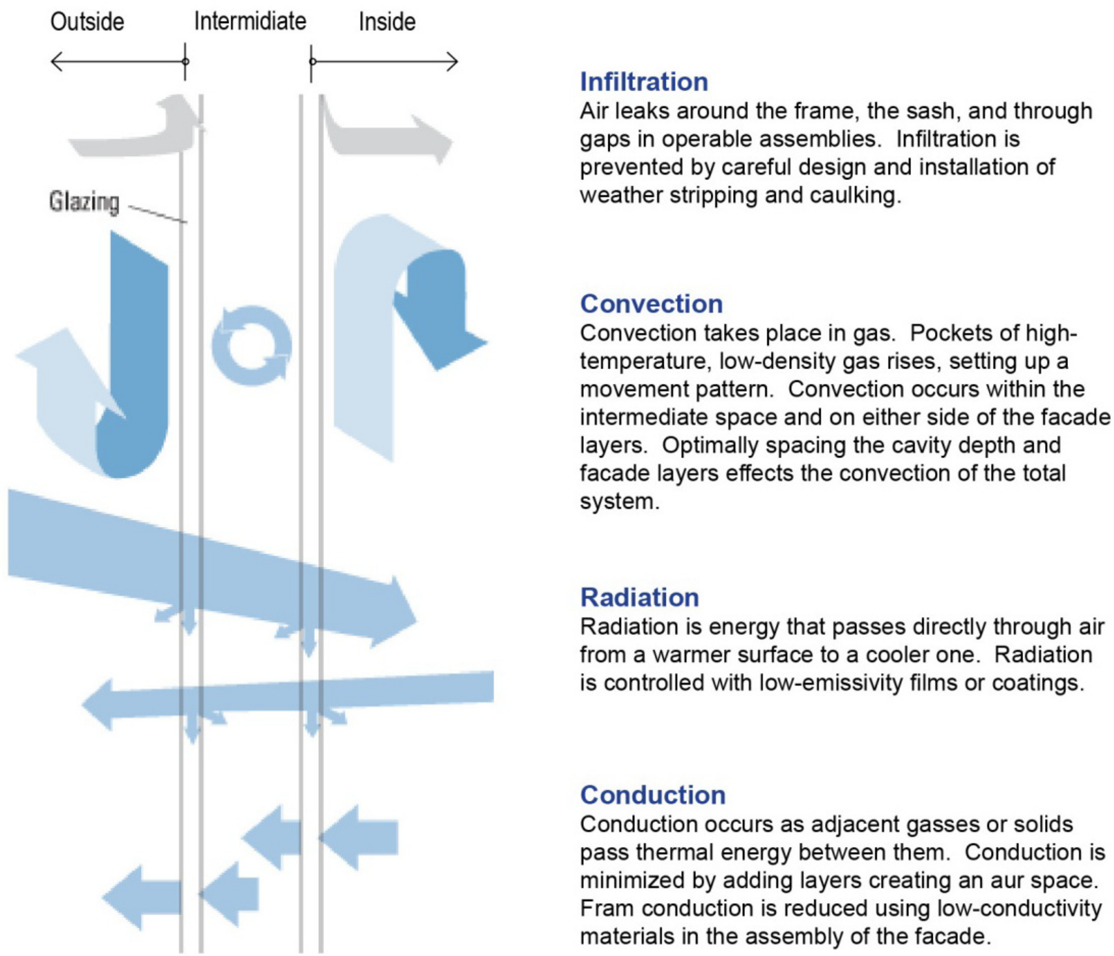

Fig 3.4: Various heat transfer methods through double glazing.

The design of a solar shading system should also consider the orientation of the building's façade. On the southern facing façade, horizontal shading devices should be implemented to block high sun angles. This technique allows for natural light to defuse into the building through the façade and reduce the amount of artificial lighting needed within the space. Adequate shading can be applied by horizontal louvers, overhangs, cantilever projections, etc. During the winter months when the need for solar energy is important, the low sun angle will penetrate deep into the building, thus reducing the energy demand needed for heating. On the East and West facing facades, sunlight strikes the building at a lower angle. This low sun angle can be mitigated with the use of vertical shading devices. By setting the angle of the louvers in relation to the location of the sun, peak optimization can be achieved by reducing the amount of direct sunlight while retaining views to the outside. East and West window shading with the use of vertical shading devices such as walls and fins can also help effectively reduce solar heat gains. The proportion of window area of the building depends on the type of solar shading. Larger window areas will often require a higher level of shading where as a smaller area of window surface only requires substantially smaller strategies.

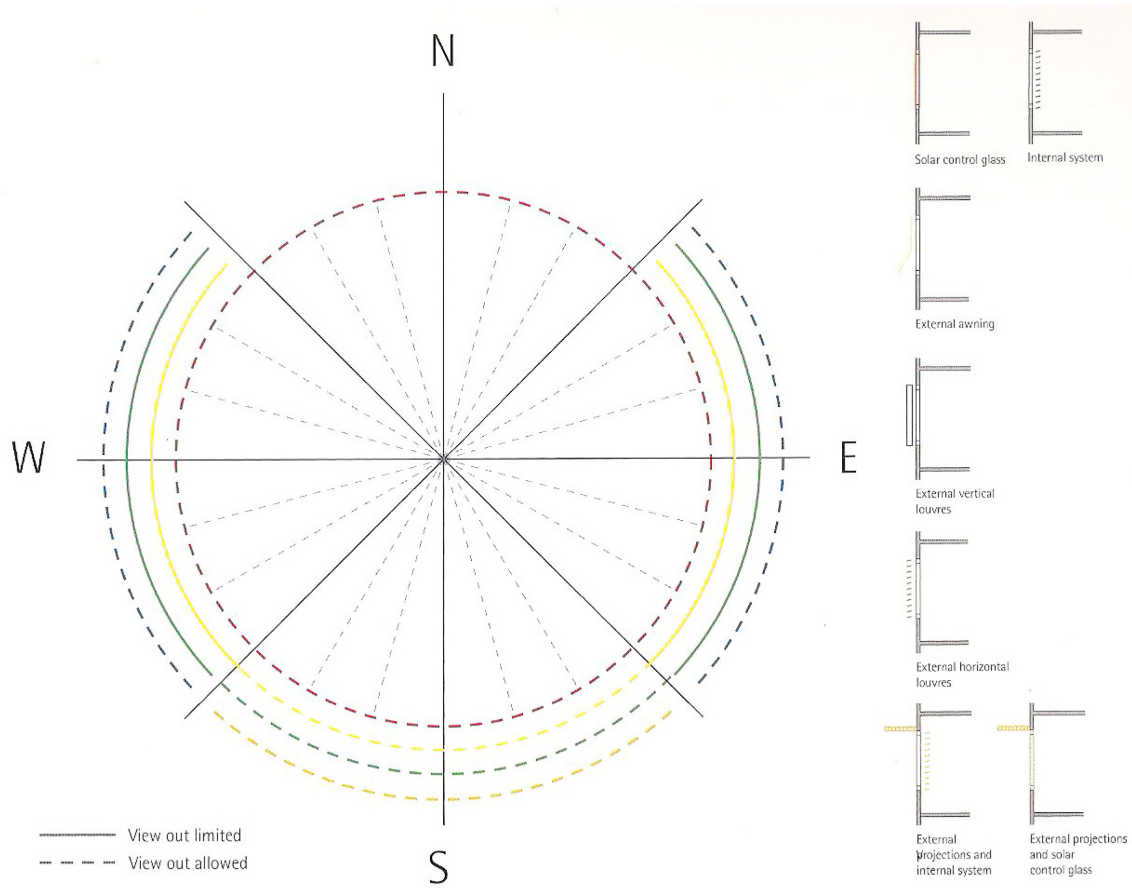

Fig. 3.5: Application of solar screening systems for various orientations

Having control over solar shading devices can have a huge effect on optimizing room temperatures throughout the day. The efficiency of a fixed shading device depends on the location of the suns angle in relation to the external surface. If the shading device is fixed, this can lead to a static condition that does not relate to the complex changes in solar angle and orientation which often results in a "one size fits all" solution. As a result, this can lead to an unpleasant room temperature despite the use of well-designed solar screens. Therefore solar shading devices should have the ability to respond to internal room temperatures in a more effective manner. If the room temperature limit is reached, solar shades can close to prevent the infiltration of additional heat gain. In contrast, when the room temperature falls below minimal standards, shading devices can be automated to open and allow for solar gains to enter the building in an attempt to generate and retain heat. These adjustments must be made automatic as users will not normally adjust solar shading to control a rooms temperature. As a result, a 'room-temperature-controlled' solar shading device can create an optimal room temperature that actively responds to the dynamic movement of the suns location and user comfort needs.

Internal thermal comfort levels are directly affected by the sun as it related to solar radiation on exposed external surfaces. Accordingly, effective solar control strategies must be implemented as solar energy reflectors in order to mitigate the infiltration of unwanted external heat gains. With the use of computer controlled louvers and protective shading devices, the infiltration of solar energy can be systematically controlled. It is evident that many buildings today consist of some sort of solar control system, but provide little or no opportunity to actively respond to the given internal conditions. However, in the current application of the double-skin facade, the use of shading devices are often incorporated within the intermediate cavity space in order to reduce radiant heat and extract it away from the building with the use of a solar flue, a shaft that encourages vertical airflow through stack effect and thermal buoyancy to provide the mean of assisted ventilation when wind speeds are low.[39]

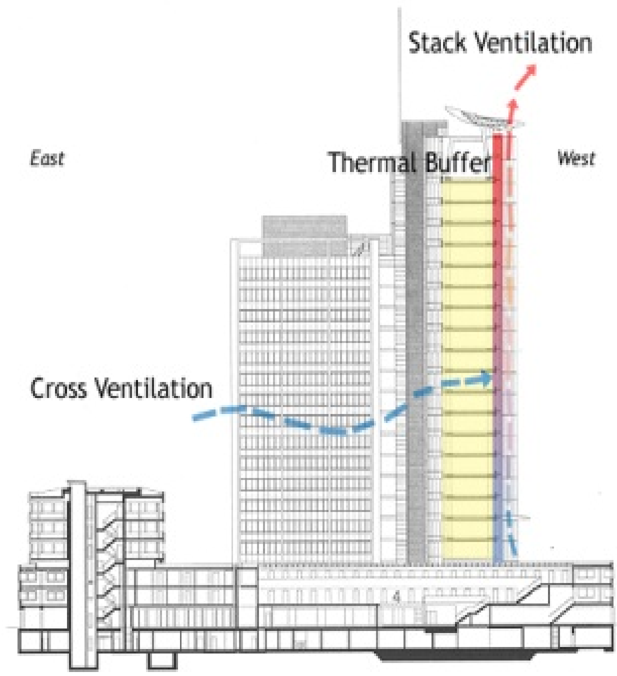

Fig. 3.6: Solar flue used in the GWS Headquarters Building.
*see case study

[39] Wigginton, Michael, and Harris, Jude. Intelligent Skins. (Italy: Elsevier, 2002) 40.

3.6. Ventilation Controllers

Ventilation can be automatically controlled within the building's facade in order to regulate the amount of air circulation within the building. These controlling elements must be incorporated into the building's envelope with the use of motorized windows, pneumatic dampers, retractable roofs and fan assists. Intelligent control systems can be implemented to control and help regulate the use of natural ventilation as it relate to the response of thermal comfort.[40]

In the case of high rise commercial buildings, natural ventilation is often achieved through the use of operable windows. These windows vary significantly in their size of opening and their ability to protect the building from the natural elements. Often these facades combine various functions of ventilation, daylighting, shading and views. With the combination of these functions, it makes it difficult to accomplish optimal performance within each category through the use of a static application.

In order to provide adequate natural ventilation, the opening of a window must be adjustable to ensure control of the dynamic movements of air flow. Conventional windows alone are usually not enough to provide the optimization of natural ventilation. Therefore additional strategies must be explored and implemented in order to provide the perfect condition in air exchange to unpredictable external conditions. The ventilation openings of the façade should allow for a dynamic air flow through the use of various ventilation elements. Basic air exchange with little infiltration of noise should be controlled. With an effective control system, ventilation can be dependent on the external environment. In this case, a temperature controlled systems would help to optimize the conditions within the internal spaces through the use of adaptability.

3.6.1. Air exchange through natural ventilation

With the use of natural ventilation it is difficult to determine the quality of the outside air that is entering the building. Whether dealing with very low or very high external temperature ranges, air pollution, and/or external noise, all supply air must be conditioned to avoid occupancy discomfort. It is also important to note that depending on the building's

[40] Wigginton, Michael, and Harris, Jude. Intelligent Skins. (Italy: Elsevier, 2002) 41.

regional climate, humidity within the introduced air must be evaluated. For that reason, designers must consider regional climactic issues as well as seasonal differences in order to deliver a comfortable introduction of naturally ventilated air. Specifically in tropical/sub-tropical climate conditions, the ventilation must carefully control incoming humidity.

Summer Ventilation:

In warm and humid climates where external temperatures are high, ventilation can play a critical role in influencing comfort within buildings. Higher temperatures of summer can cause discomfort when natural ventilation is allowing outside air temperatures to enter the building. To reduce this effect air exchange should be limited when external temperatures are higher than internal temperatures. Also during this time reducing the facades temperature is important as this can cause excessive build-up of unwanted heat. If this condition is neglected the building's façade can have a considerable amount of solar radiation that is able to transfer into the building. Therefore it is important to consider ventilation strategies the help to remove this unwanted heat away from the façade by means of convection. The amount of heat removed through ventilation is determined by the rate of air change and temperature differences, as a result an effective method of heat load removal is to utilize 'purge ventilation' in the morning.[41]

Winter Ventilation:

When external temperatures are low, natural ventilation through the façade must be conditioned to prevent discomfort. These strategies include preheating the supply air, mixing the supply air with the room air, or a combination of the two.[42] There are various ways to preheat the introduced air into the building; mechanical heating systems, waste heat from equipment, and the use of solar collectors. A conventional heating system relies on mechanical and electrical equipment to preheat and condition the air, but often results in an increase in

[41] Hausladen, Gerhard., de Saldanha, Michael., and Liedl, Petra. ClimateSkins: Building-skin Concepts that Can Do More with Less Energy. (Berlin: Birkhauser, 2008) 60.
[42] Hausladen, Gerhard., de Saldanha, Michael., and Liedl, Petra. ClimateSkins: Building-skin Concepts that Can Do More with Less Energy. (Berlin: Birkhauser, 2008) 58.

energy demand. Waste heat from computers, servers, lighting and electrical equipment can be used by locating these devices adjacent to the building's façade to allow for the external air to pass through it thus preheating the air while cooling the equipment. During the summer months, this concept can be reversed as a means of cooling the building and its equipment. Air that is ventilated through solar collectors integrated into the façade provide the best scenario as it is utilizing solar heat gains to preheat the air; a system independent from electrical needs. In most cases a mixed mode approach of air conditioning is needed because any one single system will not have the ability to solve the problem. Thus, ventilation in the winter months must be delivered through an optimized façade; a façade which has the ability to adapt to the thermal comfort demands of the internal environment.

Night Ventilation:

With the use of nighttime ventilation, the façade of the building would allow for the cool air temperature to remove unwanted heat from the interior of the building. This technique is an effective way of venting the building from the built-up heat from the day before without wasting energy; a simple night cooling mode may save around 40% of the cooling capacity and energy.[43] Controlled ventilation openings at night allow the cooling performance to be optimized and helps avoid both high and low temperatures in the morning hours. In order to increase the efficiency of this effect, a thermal storage mass such as concrete slabs can be exposed to help stabilize thermal differentials. Various built examples including the San Francisco Federal Building by Morphosis demonstrate the capability this technique will have on reducing thermal comfort demands.

Often times it is evident that mechanically controlled buildings are designed to disregard the dynamic changes in the external environment and often produce an increase in energy demand. The use of conventional air conditioning and ventilation systems create a burden to the buildings energy demand. With the integration of an intelligently controlled ventilation system, internal temperatures can be improved as the building's façade can serve as an active air control element, producing the concept of a 'breathable skin'.

[43] W.J. Stec, "Symbiosis of the double-skin façade with the HVAC system," Energy and Buildings 37 (2005): 461 – 469.

4. THE DOUBLE-SKIN FACADE

In recent years many designers have come to realize that the external envelope of a building is not static, yet a dynamic skin which interacts between the environment and building services in order to provide optimal thermal comfort and reduce the building's energy consumption. As a result, there has been a very progressive movement to create state of the art, intelligent environmental facades. From the creation of the first double façade concept by Le Corbusier, to the high-performance facades systems buildings use today, the evolution of the double-skin façade had been the forefront of the design of 'Intelligent Environmental Skins'. With an increasing demand for highly glazed facades within high rise commercial buildings, emphasis must be placed on energy consumption and thermal stability in the design of building envelopes. Due to the fact that the double-skin façade is currently the emphasis for many designers when considering a high-performance solution, a brief understanding of the system must be conducted. It is important to realize that even though this method of façade construction is the focus of this research, it may not be a perfect solution and future systems should be considered.

The double-skin façade system involves the addition of a second glazed envelope that has the ability to maximize opportunities for thermal control and improving a buildings energy performance.[44] Historically the implementation of a double-skin façade within high rise commercial buildings is commonly found in European architecture, yet it is now becoming apparent that this trend has now been adapted within the United States. Research has shown that traditionally the use of the double-skin façade is mostly driven by:[45]

- The aesthetic desire for an all glass façade that leads to increased transparency
- The practical need for improved indoor environment
- The need for improving the acoustics in buildings located in noise polluted areas
- The reduction of energy use during the occupation of a building

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[44] Wigginton, Michael, and Harris, Jude, Intelligent Skins. (Italy: Elsevier, 2002) 41.
[45] Poirazis, Harris, "Double-skin Facades for Office Buildings." (PhD diss., Lund Institute of Technology, 2004.)

Although this may be the case, a new concept of the double-skin façade is now becoming evident with the application of 'intelligence' as it relates to the possibility for the building's façade to actively adapt and respond to the external environment. With the application of 'intelligent features', a deeper understanding of the complexity of the double-skin façade and its ability to actively affect the various functions of the building (i.e. daylighting, ventilation, indoor air quality, thermal comfort, energy efficiency, etc.) can now be explored. Because the use of a double-skin façade system can address an assortment of functions of the buildings systems, it is important for this study to identify the specific functions of a double-skin façade and the impacts of the systems as they relate to thermal performance. The double-skin façade can act as an 'active façade' reducing solar gains through the use of a natural stack effect within the cavity in order to naturally ventilate unwanted solar radiation. According to the Source book of the Belgian Building Research Institute (BBRI);[46]

> *"An active façade is a façade covering one or several stories constructed with multiple glazed skins. The skins can be air tight or not. In this kind of façade, the air cavity situated between the skins is naturally or mechanically ventilated. The air cavity ventilation strategy may vary with the time. Devices and systems are generally integrated in order to improve the indoor climate with active or passive techniques. Most of the time such systems are managed in semi-automatic way via control systems."*

It has become apparent that the use of the double-skin façade as an (inter)active, multi-layered element of the building envelope to control the interior climate through the use of both active and passive techniques has become realized. As the impact of thermal comfort of the building depends on numerous components of the building (i.e. façade, HVAC, control systems, external conditions, thermal interactions, etc.) exploration of several different façade components and their interaction must be tested. Research done at TU Delft focused on creating a symbiosis of the double-skin façade with HVAC. The article illustrates the importance of an integrated design of the building systems together with the façade; "the façade plays a role in creating the indoor comfort thus it can be considered as a

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[46] Poirazis, Harris, "Double-skin Facades for Office Buildings." (PhD diss., Lund Institute of Technology, 2004.)

component of the HVAC system". [47] It is important when designing a building's façade to consider an integrated systems approach as it will affect the level of thermal performance of the internal environment. An intelligent environmental façade, in the form of a double-skin, must integrate the various components that involve thermal performance and how these systems interact with each other as conditions within the environment change. The thermal and energy performance of the double-skin façade greatly depend on the way in which the cavity air is used.

Fig. 4.1: The double-skin façade and its components.

4.1. Overall Performance

The energy performance of the double-skin façade critically depends on its ability to reduce thermal loss, the ability to improve thermal stability through ventilation, the position of the shading devices within the cavity and the ability to remove absorbed solar heat. A study titled "Energy Performance Assessment of Multiple Skin Facades" by Saelens, Carmeliet and Hens, concludes that the advantages of the double-skin façade must be combined as well as it

[47] W.J. Stec, "Symbiosis of the double-skin façade with the HVAC system," Energy and Buildings 37 (2005): 461 –469.

must have the ability to change the systems settings according to the given environmental situation in order to provide optimal energy performance:[48]

> *"It is shown that it is possible to improve the building's energy efficiency in some way by using multiple skin facades. Unfortunately, most typologies are incapable of lowering both the annual heating and cooling demand. Only by combining typologies or changing the system settings according to the particular situation, a substantial overall improvement over the traditional insulated glazing unit with exterior shading is possible. This implies that sophisticated control mechanisms are inevitable to make multiple skin facades work efficiently throughout the year. In order to correctly evaluate the energy efficiency an annual energy simulation focusing on both heating and cooling load is necessary.*
>
> *Furthermore, the analysis shows that the energy performance strongly depends on the way the cavity air is used. In order to correctly evaluate the energy efficiency of multiple skin facades, it is imperative not only to study the transmission gains and losses but also to take into account the enthalpy change of the cavity air and to perform a whole building energy analysis".*

4.2. Types of Construction

Different ways to classify double-skin façade systems according to geometry and ventilation concept established by the Environmental Engineering firm of Battle McCarthy in Great Britain identify five primary types based on commonalities of configuration and operation. They are:

- *Category A*: Sealed Inner Skin: subdivided into mechanically ventilated cavity with controlled flue intake versus a ventilated and serviced thermal flue.

[48] Saelens, D., Carmeliet, J., & Hens, H, "Energy performance assessment of multiple skin facades," (International Journal of HVAC&R Research 9 (2), 2003.) 167-186.

- *Category B*: Operable Inner and Outer Skins: divided into single story cavity height or full building height.
- *Category C*: Operable Inner Skin with mechanically ventilated cavity with control flue intake.
- *Category D*: Sealed Cavity zoned floor to floor or with a full cavity height.
- *Category E*: Acoustic Barrier with either a massive exterior envelope or a lightweight exterior envelope.

Kragh, categorizes the double-skin facades according to the function (ventilation type) of the cavity in three types:[49]

- *Naturally Ventilated Wall*: "An extra skin is added to the outside of the building envelope. In periods with no solar radiation, the extra skin provides additional thermal insulation. In periods with solar irradiation, the skin is naturally ventilated from/to the outside by buoyancy (stack) effects - i.e. the air in the cavity rises when heated by the sun (the solar radiation must be absorbed by blinds in the cavity). Solar heat gains are reduced as the warm air is expelled to the outside. The temperature difference between the outside air and the heated air in the cavity must be significant for the system to work."
- *Active Wall*: "An extra skin is applied to the inside of the building envelope; inside return air is passing through the cavity of the façade and returning to the ventilation system. In periods with solar radiation the energy, which is absorbed by the blinds, is removed by ventilation. In periods with heating loads, solar energy can be recovered by means of heat exchangers. Both during cold periods with no or little solar irradiation and during periods with solar gains or cooling loads, the surface temperature of the inner glass is kept close to room temperature, leading to increased occupant comfort in the perimeter zone, near the façade. This type of façade is recommended for cold climates, because of the increased comfort during the cold season and the possible recovery of solar energy."

[49] Kragh, M. Building Envelopes and Environmental Systems. Paper presented at Modern Façades of Office Buildings Delft Technical University, the Netherlands

- *Interactive Wall*: "The principle of the interactive is much like that of the naturally ventilated wall with the significant difference that the ventilation is forced. This means that the system works in situations with high ambient temperatures, as it does not depend on the stack effect alone. The system is thus ideal for hot climates with high cooling loads. During cold periods with no solar irradiation (e.g. during night-time) the ventilation can be minimized for increased thermal insulation. Apart from the advantages in terms of solar and thermal performance the system allows the use of operable windows for natural ventilation, even in high-rise buildings".

Oesterle categorizes the double-skin facades in considering the geometry type of the cavity section. The types are described as:[50]

- *Box window type*: In this example horizontal; and vertical partitions divide the façade in smaller, independent boxes.
- *Shaft box type*: In this example a set of box window elements are placed in the façade. These elements are then connected by vertical shafts situated in the façade to ensure an increased stack effect.
- *Corridor façade*: Horizontal partitioning is implemented for fire security or ventilation reasons.
- *Multi story double-skin façade*: A system where no horizontal or vertical partitioning exists between the two skins. The air cavity ventilation is made possible by large openings near the floor and the roof of the building.

The BBRI, suggests a more detailed way to classify the active facades according to the:

- Type of ventilation
    - Natural
    - Mechanical
- Origin of the airflow
    - From inside
    - From outside
- Destination of the airflow
    - Towards inside
    - Towards outside

[50] Oesterle, E., Lieb, R-D., Lutz, M., & Heusler, W. Double-skin Facades – Integrated Planning. Prestel Verlag: Munich, Germany.

- Airflow direction
  - To the top
  - To the bottom (only in case of mechanical ventilation)
- Width of the air cavity
  - Narrow (10 - 20 cm)
  - Wide (0.5 – 1m)
- Partitioning
  - Horizontal (at the level of each story)
  - No horizontal partitioning

By identifying the different classifications of the double-skin façade, different cases can be considered. Even more cases could be created if the different categories were refined (i.e. cavity width, shading devices, etc.) Although this way of categorizing can be very precise, the increased number of categories can be confusing.

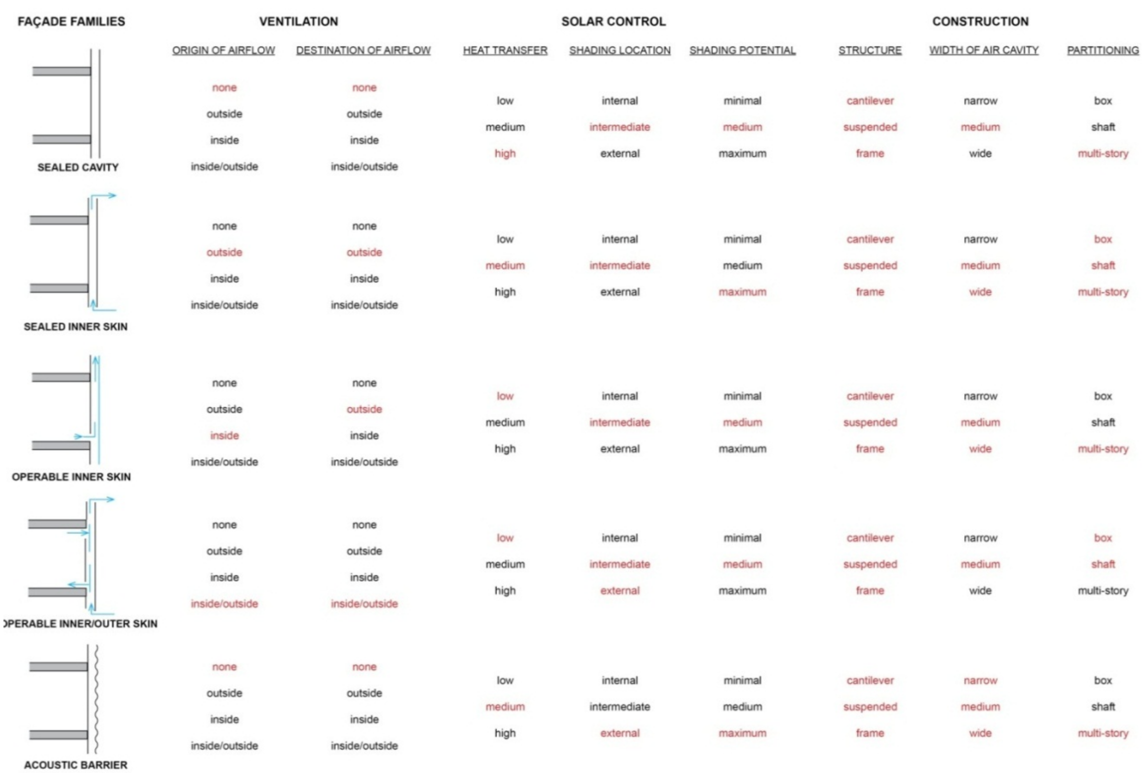

Fig. 4.2.: Comparative matrix based on façade classifications.

4.3. Thermal Insulation

One argument frequently put in favor of double-skin facades is that the outer skin provides greater thermal insulation. The buffer effect can result in considerable advantages specifically within warm and humid climates. It is also argued that providing shading and ventilation of the intermediate space between the inner and outer skins means that the system will present no thermal problems.

In Hawai`i's climate, a double-skin construction offers certain advantages if the winds acting on a high rise building provide adequate ventilation of the intermediate space. Compared to single-layered facades, the double-skin construction can achieve a comfortable degree of thermal insulation; but when the two layers are designed with poor performance fully glazed skins, the cooling loads will increase in proportion to the area of glazing. The airtightness of the façade also contributes to the thermal insulation performance. Thus, it will be necessary to consider what action can be taken for an appropriate reaction.

4.3.1. Heat Transmission

In a double-skin façade, various types of heat-transmission come into action simultaneously and overlap with each other. Conduction occurs wherever there are adjacent objects in the façade. If the objects are placed far apart, there will be a low degree of conduction. In contrast, if they were in contact with each other, high conductance values will occur. It is also important to note that gases are relatively poor heat conductors which are why intermediate layers of air in the façade provide good thermal insulation. The process known as convection refers to heat transmission via air movement. Since warmer air is lighter than cooler air, they rise towards the top of the space. This is known as free convection as opposed to forced convection, where the movement of air is caused by external forces. In addition, heat can also be transmitted by radiation. It is in this form of heat transmission that most of the heat from the sun enters the building.

4.3.2. Efficiency of Shading

The façade construction is divided into various layers by an intermediate space. The positioning of the shading within its construction plays a major role in the distribution of heat gains in the intermediate space. A narrow space will heat up faster than a wider one. If the shading device is located just in front of the inner façade and this air space is not properly ventilated, the air in front of the window can heat up considerably. Therefore, the shading device should be positioned on the outer side of the construction with good ventilation to the outside environment above and below it. To avoid excessive heating and thermal loading of adjacent layers it should not be too close to them as well. Determining the effective characteristics of the shading device for each case can cause considerable problems since the properties can vary considerably. The shading device can provide a complete screening of the area behind it or it may be cut-off in various positions. Levels of permeability to light are also based on the type of shading used. Where shading is set at a steeper angle, a greater degree of shading occurs but a reduced rate of light transmission results. It is worth investigating the characteristics of the combination of glass and shading, as well as proposed ventilation of the intermediate space. This relationship is based on a case by case basis in order to obtain the necessary outcome.

By drawing up the thermal balance for a room at the height of summer one can begin to identify loads that are directly caused by the façade. The intensity of the insolation, which acts as a cooling load in the room is directly influenced by the façade construction. It depends on the area of glazing in the façade, the quality of the shading and the efficiency of the natural room ventilation. In the case of double-skin facades, additional factors will have to be considered; the heating up of the intermediate space and the thermal gains that lead. These gains occur directly in the form of warm air flowing into the interior space.

The opportunity for solar shading by double-skin facades and the thermal properties of the outer layers can be exploited to create a high level of thermal insulation. As a result, it is important in the design of the double-skin façade to take advantage of this buffering, along with ventilation in order to reduce heat transmission into the interior environment.

4.4. Airflow

The thermal behavior of double-skin facades is significantly affected by the airflow within the system. The flow of air towards, around and within the assembly greatly affects the aerodynamics of the overall performance system.

4.4.1. Basics

Pressure differences are always the driving force of air currents within the assembly. Air flows from a space with high pressure to one with low pressure in order to create a state of equilibrium. In the context of the double-skin façade, there are three main causes for pressure differences:

- *Pressure differences caused by mechanical systems (fan assist)*: A fan is one of the most common means of moving air mechanically. Its effect is commonly used within this type of assembly, pushing the air within the intermediate space in a certain direction.

- *Pressure differences caused by wind (driving force)*: Wind can have a major influence on air currents within the intermediate space. Its distribution is dependent of wind speed, size of opening and flow resistance or losses. Wind and its effect play a significant role for the planning of the façade. If properly designed, wind flowing over the façade can create pressure differences between inlet and outlet thus causing air movement.

- *Pressure differences caused by thermal buoyancy (stack effect)*: As a result of insolation, the air within the intermediate space becomes warmer than the outside air. The air inside this space is there for lighter than the outside air, so the process of equalization in the system occurs. The cooler, external air forces its way into the intermediate space. The warmer air within the space is lighter and rises where the heat is ejected. Typical pressure differences between the intermediate space and the outside air results in thermal uplift.

The pressure differences responsible for thermal uplift within the double-skin façade have been discussed. The pressure differences between the upper and lower openings are regarded as forces acting on the open areas, where the driving force is the result of pressure differences in relation to opining area. Air currents within the space and details of the air flow through inlet and outlet openings have a considerable influence on the overall airflow pattern. Airflow passing through an opening and the specific geometry of the façade assembly can result in losses due to flow resistance. It is important to be aware of this when designing the flow of air within the assembly.

The air velocity and the type of flow inside the cavity depend on:

- The depth of the cavity
- The type of interior openings
- Type of exterior openings

Simulations of the façade cavity are necessary if one wants to calculate the specific path of the ventilation as well as temperature differences at different heights in the cavity. In addition, the specific air flow patterns are critical in the development of the façade:

- Type of double-skin façade: box window, shaft, multi-story, etc.
- Geometry of the façade: width of openings, height and width of the cavity, etc.
- Layer composition: proper placement and combination of layer type and shading device.
- Ventilation strategy: origin and destination of the air inside the cavity, natural/mechanical ventilation, etc.

For naturally ventilated façade systems, the outside air is brought into the cavity and exhausted by two means: wind pressure and/or stack effect. In the absence of wind, the cavity can still be ventilated due to stack effect. As air enters the inlet, it becomes heated and less dense and thermally buoyant. As a result, air will flow into the inlet and out the outlet while removing heat. There is a potential for stack effect and wind driven pressure to be counteractive, thus the air path and exterior openings need to be properly sized and configured to insure that these two means work together. If not properly understood, the preheated air and the solar heat gain within the cavity will not be removed efficiently and will increase cavity temperatures.

In the case where natural ventilation of the interior space is used, specific requirements must be taken into account. Oesterle states that a 2% opening area as required by guidelines for workplaces in standard offices should be available for both intake and extract and the vertical distance between the openings should be as large as possible.[51] In the case of double-skin facades, this value provides a reference point unto which one should take into account. However, it will be necessary to prove that adequate room ventilation is achieved. This proves that for reliable extraction of heat from the interior space and the intermediate cavity is a critical aspect that should not be neglected. In dealing with ventilation of the interior space, regulations govern the amount of air changes required. In offices, HVAC systems will provide roughly 2 to 3 air changes per hour. This hourly air change rate (ACR) is defined as the relationship between the volume of air supplied per hour and the volume of the space. Therefor where natural ventilation is used, a specific air change rate should be established when the inner facade is open.

In the principles outlined above, the main forces causing free ventilation are wind and thermal uplift. In the context of hot climates, sufficient removal of air within the system is critical. The air exchange between the environment and the cavity is dependent on wind pressure on the buildings skin, stack effect and the size of the openings. In a naturally ventilated façade, the depth of the façade has to be determined precisely. The ventilation of interior rooms is achieved by opening appropriate valves. The allowed height of partitions depends on cavity sizing; however, the upper limit is given by the allowed air temperature rise in the cavity (i.e. air temperatures will increase relative to the height of the cavity). A description of the function and the air flow of the cavity is relation to construction parameters are presented by Oesterle. [52] It is noted that only when the cavity between façade skins is less than 15 inches, significant pressure losses will occur. As a result, the design of the intermediate space must be larger than 15 inches so that there are no major resistances to the air flow of the system.

4.5. Daylight

Daylight is one of the most important requirements for a productive work environment. Good natural lighting and unobstructed views out of the building belong to the minimum standards required for workplaces. In terms of natural lighting techniques and the double-skin

[51] Oesterle, E., Lieb, R-D., Lutz, M., & Heusler, W. Double-skin Facades – Integrated Planning. Prestel Verlag: Munich, Germany.
[52] Oesterle, E., Lieb, R-D., Lutz, M., & Heusler, W. Double-skin Facades – Integrated Planning. Prestel Verlag: Munich, Germany.

façade, there is no major difference between them and single skin facades. However, there are some differences when it comes to those specific with the double-skin façade. These include:

- The reduction of the quality of light entering the rooms as a result of the additional external skin.
- The additional effective room depth caused by the façade projection.
- The installation of light reflective elements in the façade intermediate space.

The additional outer layer implied by a double-skin automatically means a worsening of natural light conditions. The traditional addition of glazing on the outer layer consists of a single layer of glass. Thus, the level of daylight transmitted will be reduced relative to the application of additional layers to the existing façade. The measure of the quality of natural light is the daylight factor, describing the light intensity on a horizontal plane in the interior space of a building. For office spaces, a light intensity of 300 to 500 lux is recommended.   Thus, it is similarly important to recognize acceptable lighting levels in regards to double-skin composition.

One can optimize daylight levels with the use of light-reflecting systems. The level of effectiveness is based on the redistribution of the daylight into the depths of the internal space. In most cases, many double-skin systems implement light colored, reflecting louvers within the cavity of the façade. One of the major problems is selecting and positioning these elements within the façade plane with the potential disruption of air flow within the space. Additionally, increasing the brightness in the room with reflective elements will imply a degree of shading in the area near the facade.

4.6. Sound Insulation

The external façade layer can considerably improve the sound insulation of a building, especially with screening external noise like a protective wall. Thus, many describe double-skin facades as an acoustic screen, valuable where external noise pollution may be considerable. The external plane screens off noise by reflection with three main results:

- The noise level from external sources is lower behind the outer skin, improving the sound insulation of the façade as a whole. If windows on the inner skin are opened, they are exposed to this reduced level of noise.

- Sound will not be reflected by open areas in the façade. The size of these openings helps to determine the potential screening effect of the outer skin. Because these openings are critical for the ventilation of the intermediate space, there needs to be an understanding of the level of sound insulation and the needs of ventilation.

- Also, sound from the interior of the building will also be reflected back by the skin. This can cause undesirable sound transmission from room to room.

As a result, double-skin facades are a valuable response to controlling traffic noise in urban areas. In some cases, a double-skin façade will make natural ventilation possible where the external noise level may be too high. This of course depends on the external air being of acceptable quality to allow for direct ventilation.

4.7. Fire Protection

Double-skin façade construction is still not covered by building regulations so very little information exists on the design of the façade in relation to fire protection. As a result, there is no way of assuring the safety of this form of construction with issues of fire. It is for this reason that specific assessment will have to be made for each scheme as well as approval from appropriate building authorities. However, basic treatment and the protection of double-skins are described.

4.7.1. Fire Protection Risks

Localization

When the fire is minimal and no thermal destruction of the outer façade material occurs, it may be difficult to localize the fire. Also, it is almost impossible for occupants in the room to break the outer layer. The use of the double-skin also makes access for the fire department from the outside much more difficult.

Smoke in the facades intermediate space

Under certain circumstances, the inlet and outlet openings in the outer façade may not provide adequate means of removing smoke from the intermediate space. As a result, smoke escaping from the inner façade into the intermediate space between the two skins may spread both vertically and horizontally. Therefore it is necessary to activate the natural air flow of air through the facade space.

Fire Spread

The risk of fire spread can occur when flames escape through the inner façade into the intermediate space through a leap frog effect. The possible spread of fire both vertically and horizontally will greatly depend on the divisions within the space. As a result, the use of non-combustible materials is required for the divisions within the façade. Also, regulations relating to the façade construction require individual elements of the outer skin to be fixed independently from each other.

If the overall risk for a building with double-skin facades is exceeded, additional fire-safety measures will be required. Automatic fire-warning systems and smoke detectors provide and important level of fire-protection. Where the potential risk is high, sprinkler installation will be necessary for the rooms adjacent to the facade and will prevent the spread of fire through the intermediate space. In specific cases, a sprinkler system may be necessary in the façade itself.

4.8. Economic Viability

The economic viability of implementing a double-skin façade is a very controversial topic. Opinions range from too high a costs to economically viable due to the energy saving. These arguments are generalized and only take into account initial capital cost and energy saving. It is well known that double-skin facades are more expensive than single facades. The double-skin is a fairly complex application and thus results in higher costs. The underlying question is whether the savings accumulating over the use of the building with a double-skin façade can compensate for the higher capital investment cost. Unfortunately, research into the economic viability of double-skin facades is quite limited. However, with a basic understanding of the system, one can begin to establish a basis for an assessment of the economic viability of double-skin facades. Economic analysis of the façade should take into account the following cost components:

- Investment cost: Façade construction, materiality, control systems, shading devices, fire protection measures, etc.
- Operation and Maintenance: Cleaning of the system, energy costs of the system, operation, inspection, service and maintenance, etc.

With the investigation of the cost-effectiveness of double-skin facades, the non-monetary aspects of occupancy comfort and building aesthetics and functionality play a major role. Other cost benefits that relate to the functionality of the system should also be analyzed. A comparison between concepts for single skin and double-skin facades will expose the differences in the functional values. In relation to comfort, double-skin construction can provide natural window ventilation where unfavorable conditions are present. Improvement in the level of comfort of the interior space will lead to occupancy satisfaction and increase productivity, a factor that possibly adds to the balance of the higher cost of a double-skin façade. The use of the double-skin façade can also add an improved aesthetic quality of the building. The functional value of the double-skin façade can be easily compared with a cost-benefit analysis. Oesterle goes into extensive detail with the analysis of investment costs, cost determinants, and specific procedures for economic analysis of the double-skin façade.[53]

[53] Oesterle, E., Lieb, R-D., Lutz, M., & Heusler, W. Double-skin Facades – Integrated Planning. Prestel Verlag: Munich, Germany, 2001.

4.9. Advantages and Disadvantages

Although the double-skin façade system may be considered as one of the key elements in which makes up an environmental skin, an analysis of the desired goals and weaknesses of this system must be addressed. In order to clearly evaluate the effectiveness of the double-skin façade as it relates to the topic of thermal performance control, both advantages and disadvantages should be understood.

Advantages:

- Thermal Insulation – The double-skin façade system can provide greater thermal insulation due to the outer skin.
- Low U-Value– Low thermal transmission (U-value) and the low solar heat gain coefficient.
- High R-Value – High thermal resistance (R-value) due to the added layer of insulation.
- Natural Ventilation – The double-skin façade system has the ability to allow for natural or fan assisted ventilation.
- Nighttime Ventilation – Ability to pre-cool the offices during the night using natural ventilation.

Disadvantages:

- Potential overheating – If the double-skin façade is not properly designed it is likely that the temperature of the air within the cavity will increase overheating of the interior space.
- Increased solar gains – Due the fact that the double-skin façade often demonstrates a highly glazed surface, solar radiation can affect the large areas of glazing.
- Increased air flow – An increase speed in air flow within the cavity space can cause potential pressure differences between office spaces in the event of natural ventilation.
- Higher construction costs – The construction of the outer layer and the space between the two skins is more expensive than single skin forms.
- Maintenance – Comparing a double-skin façade to a single skin, the double-skin has a higher cost regarding cleaning, operation, servicing and maintenance.

4.10. Case Studies

The purpose of the case study section is to provide references for built examples of double-skin facades and to identify the various intelligent features implemented within each building application. In relation to the research project, emphasis will be placed on the methods of environmental control of the building's façade as it relates to thermal performance regulation.

The intention of this study is to recognize the key characteristics of the intelligent façade and begin to analyze the components in each application as they relate to thermal control. A brief overview begins each case study detailing the background information of the project as well as identifying the location, project architect and the key intelligent characteristics of the design. Further investigation will concentrate on the specific features that the system implements and evaluate them as to the level of control they have over the influence of the internal climactic conditions.

The following case studies integrate intelligent façade strategies with the overall building design and building systems to achieve high performance – energy performance as well as thermal comfort. Although many applications of the 'Intelligent Building Skin' today have been recognized through the use of a double-skin façade, it is important to note that the 'Environmental Skin' is a multi-layered aspect of façade design and must not be limited in its design to achieve a high level of building performance.

4.10.1 GWS Headquarters

Location: Berlin, Germany
Date of completion: 1999
Architect: Sauerbruch & Hutton Architecture
Dates: 1990 - 1999
Client: Gemeinnutzige Siedlungs und Wohnungsbaugesellschaft (GWS)

Introduction

The GWS Headquarters Building is a collection of multiple spatial volumes including an existing office tower, a three story bar, and a new tower. While the GWS Headquarters is elegant in its simplicity of form and function, the design showcases a highly technical intelligent façade design. This highly transparent and dynamic façade of the new office tower is the most important feature of the project as the implementation of an intelligent skin allows the building to respond to both regional and local environmental issues. A colorful array of automated shading panels located within the cavity of the west facing double-skin façade controls solar heat gain and daylighting throughout the day. Natural ventilation is utilized on the easterly façade as it is able to pass through the building and be vented to the west. The western double-skin façade cavity serves as a solar flue, drawing air up and out of the building regulated by dampers controlled by the building management system providing for precise internal environmental control. Individual

Fig. 4.3: GWS Headquarters Building, Sauerbruch & Hutton Architecture.

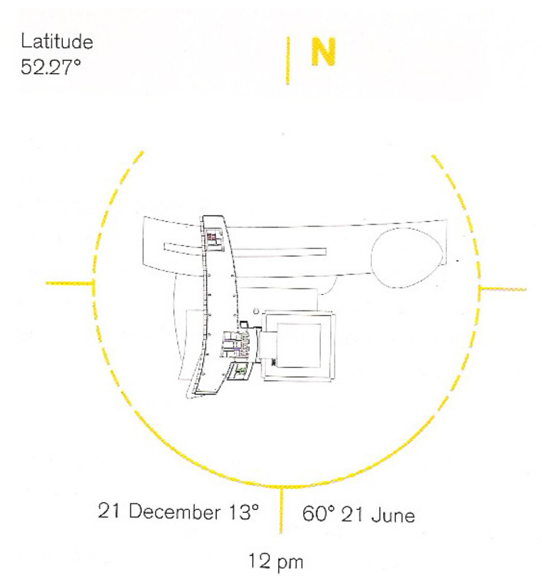

Fig. 4.4: Sun path diagram.

occupant control is made possible by the integration of intelligent systems that allow for an override of both the airflow and shading devices. The system also provides communication with the occupant in each individual office as it displays a green or red light recommending whether mechanical or natural ventilation should be used. The buildings intelligent features include a building management system, environmental data tracking, solar control, natural ventilation, nighttime cooling, occupancy control, and the implementation of the double-skin façade.

Design Strategies

The central feature of the GWS Headquarters is the concept of low energy design strategies implemented through the application of the double-skin façade of the west side of the building. As a key component of the building, this 'Intelligent Skin' acts as a multi-layered aspect of façade design integrating various strategies; it provides weather protection, prevents thermal loss, and acts as a thermal flue which promotes natural ventilation. The east façade is comprised of triple-glazed windows with blinds staggered between them. A double-skin façade is located on the west side of the building and features an interior double pane window that can be both manually and automatically operated. The internal cavity space of the double-skin façade is 3 feet wide.

*Control Systems***:**

The building management system (BMS) is the main controller of the key features of the intelligent façade system. The BMS controls the air flow within the double-skin cavity by opening and closing the dampers at the top and bottom of the façade. The BMS also has the capability of communicating to the occupant in each individual office through red

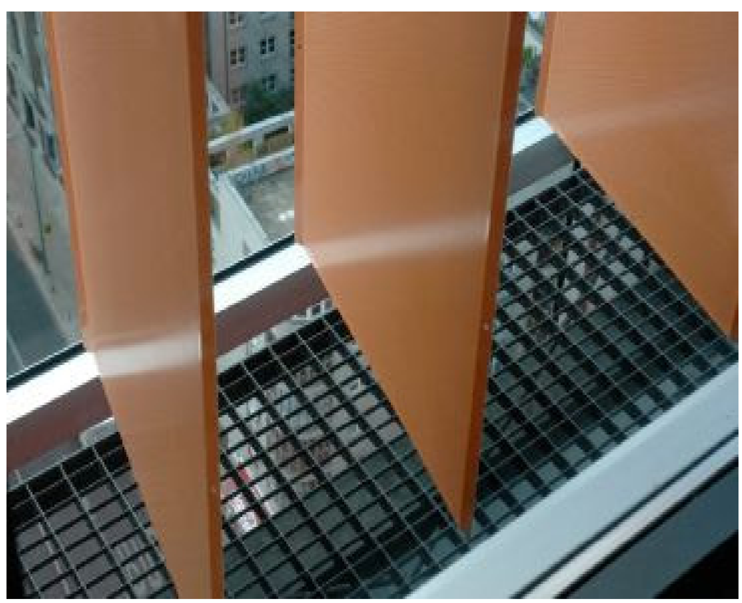

Fig. 4.5: Dampers located in the double-skin cavity.

and green light notifications.[54] The ability for user control is maximized by giving individual occupants the option to override the system; this allows for individualized control of each space to create a personalized internal condition which caters to each occupant's specific need.

Ventilation Control:

The ventilation strategy of this building allows for cross ventilation of external air to enter through the east façade. The double-skin façade of the west acts as a 20-story high shaft encouraging vertical airflow through stack effect and thermal buoyancy and also provides assisted ventilation when wind speeds are low with the use of a solar flue.[55] As a result, the façade has the ability to control wind speeds throughout the office through the use of internal self-adjustments. A mixed mode system allows for mechanical ventilation to provide necessary air changes in the case where operable windows need to be closed due to extreme external environmental conditions. With the integration of the building management system, the building can determine whether to turn on the mechanical system or allow for occupants to determine individual zones within the building to either naturally ventilate or mechanically ventilate these spaces. This feature might prove

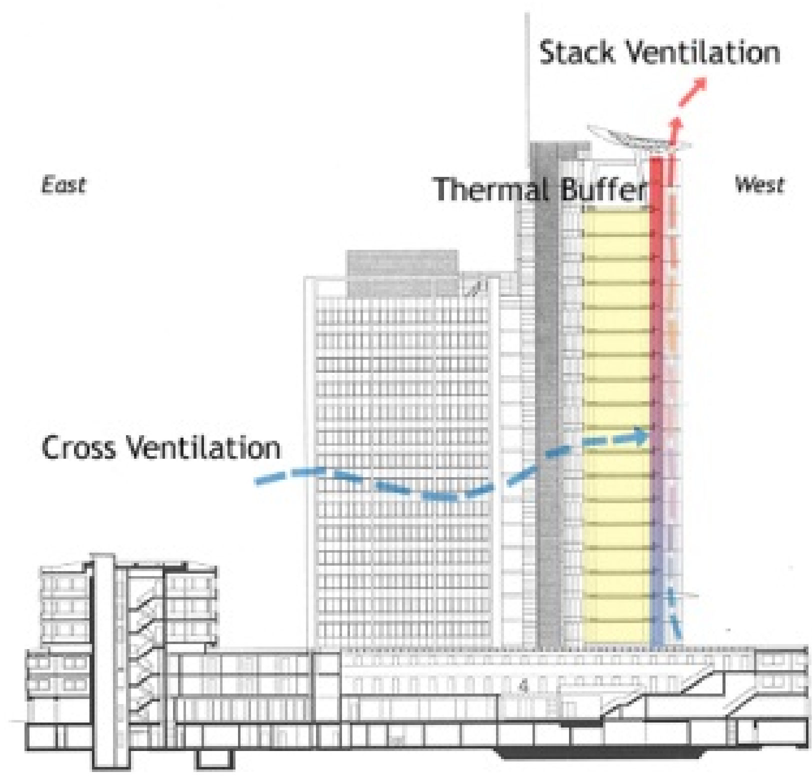

Fig. 4.6: GWS Headquarters stack ventilation diagram.

[54] Clemmetsen, N., W. Muller, and C. Trott. 2000. "GSW Headquarters, Berlin." Arup Journal, February 2000, pp. 8-12.
[55] LBNL. "High-Performance Commercial Building Facades – Building Case Studies." Accessed April 16, 2011. http://gaia.lbl.gov/hpbf/casest_f.htm

useful as mechanical and electrical equipment can be zoned in a space which must be mechanically ventilated through the year yet allow for other zones to be naturally ventilated.

Solar Control:

The double-skin façade on the west side of the building is equipped with perforated vertically pivoting and sliding panels (Fig 5.5). These panels protect the building from excessive external solar radiation as well as serve as a control device for daylight adjustments. Due to the fact that these vertical louvers are located with the cavity of the facade, ventilation is used to drive excessive heat away from the building. In the case where this heat is desirable, a heat recovery system is available and allows for trapped heat to enter the building through the ventilation system. On the easterly façade, integral blinds are located on the exterior face of the building to protect the glazing from unwanted solar heat gains as well as control daylighting.

Fig. 4.7: GWS Headquarters vertically pivoting and sliding panels.

The glazing system, which gives the building its character, has an average U-value of 1.6W/m^{2}K and the external walls have a value of 0.3W/m^{2}K.[56] The western façade which is comprised of an inner double glazed window along with an outward opening vent allows internal air to enter into the stack ventilation cavity. This opening in the window is used as a control point for air flow into the cavity and throughout the building. The outer skin of the façade is a laminated single glazed panel window. The east façade has triple-glazed windows which help to deter thermal heat gains from entering the building. Mid-pane blinds and a hopper are also integrated within the façade to allow for ventilation in cold weather.

[56] Wigginton, Michael, and Harris, Jude. Intelligent Skins. (Italy: Elsevier, 2002) 51.

Key Features

- Building Management System (BMS) - The ‘brain’ of an intelligent building, receiving and processing information in order to determine an appropriate response.
- Environmental Data - The ability to collect real time environmental data and analysis of airflow paths, temperature and ventilation.
- Solar Control - Active systems that respond to solar angles, providing optimum positions for shading and reflection.
- Occupant Control: - Maximum personal control over their direct environment, allowing for manual overrides.
- Ventilation Controllers - Automatic regulation of ventilation controlled by operable elements in the building fabric.
- Heating and Temperature Controllers - Ability to reduce the energy demand of highly serviced elements of heating, ventilation and cooling through passive/interactive strategies.
- The Double-skin - A system involving the addition of a second glazed envelope which can create opportunities for maximizing daylighting and improving energy performance.

4.10.2. Stadttor (Gate City)

Location: Dusseldorf, Germany

Date of completion: 1997

Architect: Petzinka Pink und Partner

Dates: 1991 – 1997

Client: Speculative office development

Introduction

In 1991 a competition was held to design a high-rise building above a new road tunnel that brings traffic into the center of Dusseldorf. The competition was won by Petzinka Pink und Partner. The new building was to be part of a new creative mile that was proposed for the old harbor with studios, offices, and media developments. The Stadttor project is an office building that is designed to give a high quality of light to individual spaces providing an attractive work environment. The building is composed of two separate towers, connected at the top with bridges and a large atrium space of 165 feet high. The 20 story building is supported by vertical triangulate trusses which are connected to the top three floors of the building. The double-skin cavity has a depth of 4.5 feet and encloses the balcony spaces for all offices.[57]

Fig. 4.8: Stadttor, Petzinka Pink und Partner.

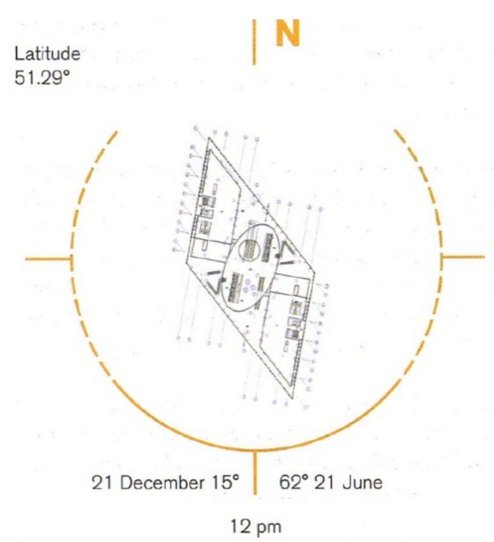

Fig. 4.9: Sun path diagram.

[57] Wigginton, Michael, and Harris, Jude. Intelligent Skins. (Italy: Elsevier, 2002) 65.

Design Strategies

The building is predominantly naturally ventilated through computer-controlled ventilation flaps which run in horizontal bands at each floor level. The BMS has sensors for wind, temperature, rain, and sun to exercise optimum control strategies for heating, cooling, and fresh air supply. The ventilated double-skin limits the required cooling loads, by ventilating away the solar heat build-up in the cavity.

Control Systems

The building is controlled by a building management system (BMS) that automatically determines whether to use natural or mechanical ventilation within the building. Natural ventilation is achieved through computer control ventilation flaps within the depth of the building envelope cavity. Venetian blinds within the cavity are lowered and raised automatically according to light and insolation levels as well as the need for nighttime insulation.

Ventilation Control

Ventilation boxes at each floor level are integrated into the depths of the façade with an automatically controlled damper. Alternate boxes act as inlet and outlet vents, with grills into the cavity from the top and bottom of the box respectively. The ventilation flaps can be completely open or closed depending on the building's needs. For natural ventilation, the users can open the inner windows manually. The ventilation flaps on the outer façade which allow air into the cavity are automatically controlled. Mechanical ventilation of the interior space is also provided through ceiling diffuser slots.

Fig. 4.10: Intermediate cavity space.

Solar Control

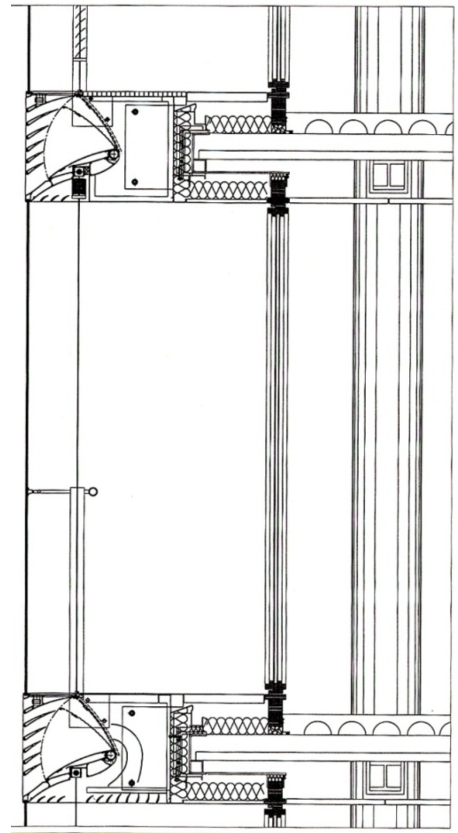

Fig. 4.11: Typical wall section detail.

Full height glazing ensures maximum exposure to daylight and views. Venetian blinds are situated 8 inches behind the outer face of the building within the double-skin cavity. The blinds are automatically lowered in response to lighting sensors located on each façade which help to indicate which particular surface the sun is shining on. Once lowered, the blind have the ability to tilt to a 45^0 to allow for maximum protection against glare that enters the building. In contrast, if there is no sun shining on that particular surface of the facade, then the blinds are raised to allow for maximum daylighting. The blinds can be automatically controlled by occupants within the space allowing them to adjust the angle of the blinds from closed, horizontal and 45^0. The 4.5 foot depth of the cavity space also helps to provide level of insulation in ensuring that most direct sunlight is prevented from entering the inhabited zone.[58]

Key Features

- Building Management System (BMS) - The 'brain' of an intelligent building, receiving and processing information in order to determine an appropriate response.
- Environmental Data - The ability to collect real time environmental data and analysis of airflow paths, temperature and ventilation.
- Solar Control - Active systems that respond to solar angles, providing optimum positions for shading and reflection.

[58] Wigginton, Michael, and Harris, Jude. Intelligent Skins. (Italy: Elsevier, 2002) 67.

- Occupant Control: - Maximum personal control over their direct environment, allowing for manual overrides.
- Ventilation Controllers - Automatic regulation of ventilation controlled by operable elements in the building fabric.
- The Double-skin - A system involving the addition of a second glazed envelope which can create opportunities for maximizing daylighting and improving energy performance.

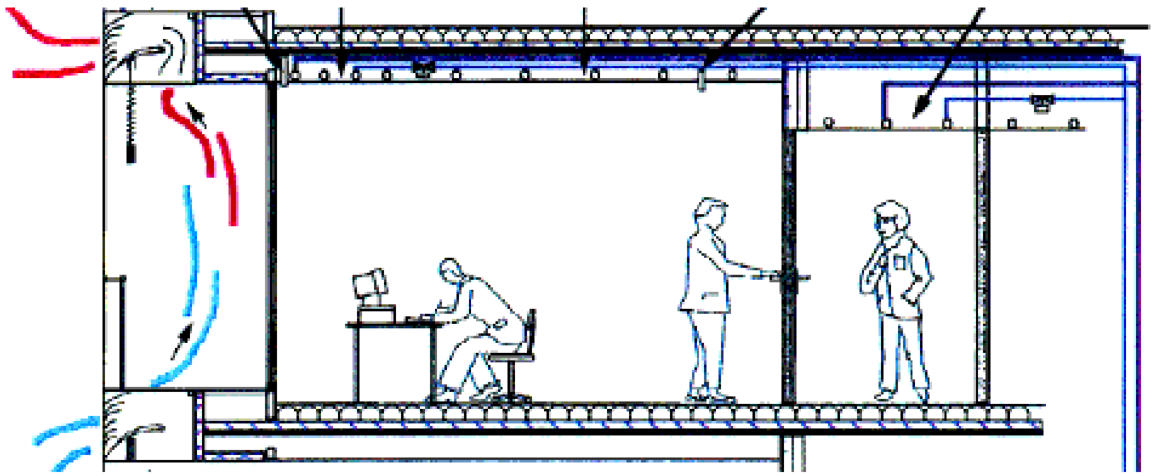

Fig. 4.12: Single story corridor ventilation strategy.

4.10.2. SUVA Insurance Company

Location: Basel, Germany
Date of completion: 1993
Architect: Herzog & de Meuron
Dates: 1988 - 1993
Client: Schweizerische Unfall-Versicherungs-Ansalt (SUVA)

Introduction

The original SUVA Insurance Company Building comprised of a six-story office building with punch-hole windows and sandstone cladding. The architects, Herzog & de Mueron were hired to retrofit the building to improve its thermal and lighting performance by overcladding the existing building while preserving the existing façade. The original sandstone cladding has been covered by a framework of glazing panels in aluminum frames. The new glazed outer skin is divided into three horizontal bands of computer controlled windows allowing for natural ventilation and an upper panel that adjusts to the suns solar angles.

Fig. 4.13: SUVA Insurance Company, Herzog & de Meuron.

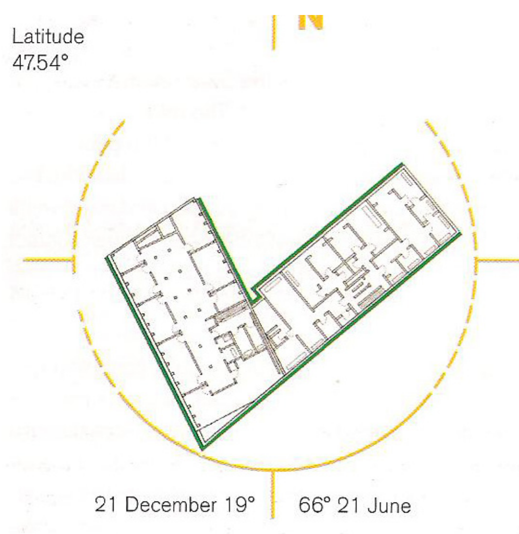

Fig. 4.14: Sun path diagram.

Design Strategies

The central design strategy of the SUVA Insurance Company building is the notion of optimizing thermal performance by implementing in the application of an 'intelligent' skin by means of a building retrofit.[59] As a key component of the building this outer skin protects the existing façade to provide enhanced

[59] Herzog & de Meuron. "The SUVA building." Accessed April 20, 2011. http://people.seas.harvard.edu/~jones/lab_arch/H_and_dM/translations/hdm_4/hdm_4.html

thermal performance, natural ventilation and daylighting. The resulting double-skin façade encloses the interior environment of the building and implements various intelligent features that can be both manually and automatically operated.

Control Systems:

The building is controlled by a central building management system (BMS). It controls the operable windows of the outer façade and the lighting systems used throughout the building. Local environmental data is captured by a weather station located on the roof of the building and provides the computer with real time data for solar radiation, wind speed and outside temperature. Sensors are also located within the façade to give accurate cavity temperature and airflow. The BMS is also able to calculate the solar azimuth and elevation based on the buildings location. Users have control over their environments with wall-switches for external panels, operable windows and local temperature control.

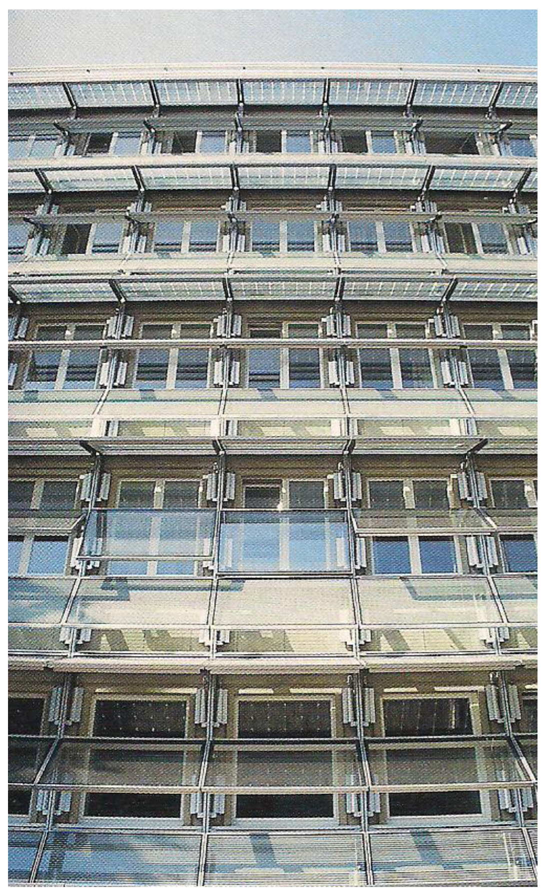
Fig. 4.15: Operable external panels.

Ventilation Control:

The building relies on both natural and mechanical ventilation for cooling. Each operable panel has the ability to open or close according to air temperature between the two skins. During summer months the outer skin opens to promote air movement throughout the building. Night time cooling is implemented by opening the panels to diffuse potential heat gained throughout the day. Occupants also have the ability to manually open the inner windows on the original building providing natural ventilation. Additionally, each window has a manual control switch which controls the operation of the outer panels. A combination of the two delivers maximum control of air flow.

Solar Control:

The glazing of the façade consists of insulated glass with adjustable prism panel that can defect solar radiation yet serve to refract the sun's rays into the building.[60] The BMS has the ability to measure the solar insolation and calculate the sun's azimuth and angle on each façade. The controlled panel then can adjust so that they are perpendicular to the solar angle providing for maximum solar protection throughout the day.

Key Features

- Building Management System (BMS) - The 'brain' of an intelligent building, receiving and processing information in order to determine an appropriate response.
- Environmental Data - The ability to collect real time environmental data and analysis of airflow paths, temperature and ventilation.
- Solar Control - Active systems that respond to solar angles, providing optimum positions for shading and reflection.
- Occupant Control: - Maximum personal control over their direct environment, allowing for manual overrides.
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- Heating and Temperature Controllers - Ability to reduce the energy demand of highly serviced elements of heating, ventilation and cooling through passive/interactive strategies.
- The Double-skin - A system involving the addition of a second glazed envelope which can create opportunities for maximizing daylighting and improving energy performance.

[60] Wigginton, Michael, and Harris, Jude. Intelligent Skins. (Italy: Elsevier, 2002) 140.

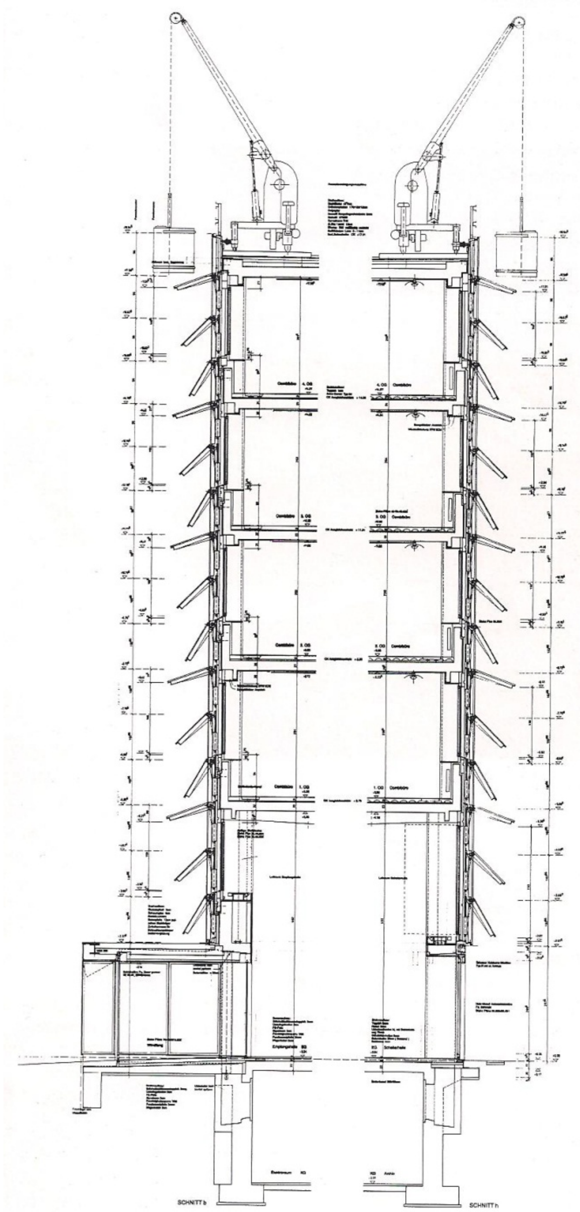


Fig. 4.16: SUVA Insurance Company building section.

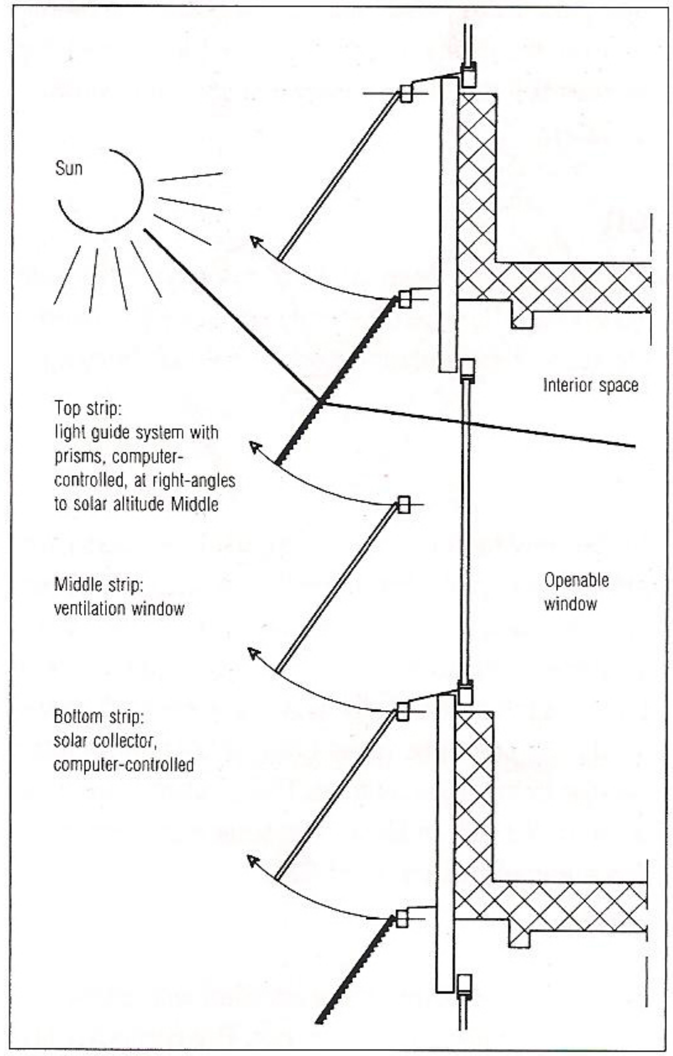


Fig. 4.17: Sectional diagram of the façade elements.

5. BUILDING STOCK

Commercial high-rise buildings with highly glazed facades in Hawai`i present overheating challenges due to high outside temperature and solar gains. Through the utilization of an intelligent skin, the need for mechanical and electrical environmental systems can be reduced or even eliminated with the implementation of double-skin facades. Within the United States there is an increasing demand in retrofitting and reusing buildings than constructing new ones. Within the office sector, retrofitting of the existing building stock will be a major area of activity within the next few years and thus the incorporation of energy efficient building skins will be significant. In the context of an increasing number of retrofitting projects and greater consideration for sustainability, architects are looking for the optimization of the existing building stock and thus need to establish comparisons between different possible variations. Because new buildings comprise of 1-5% of the total built environment, building professions have shifted their focus from new construction to retrofitting existing buildings.[61] The application of the double-skin facade does not have to be confined to new building design, yet can be implemented in refurbishing and overclading buildings with a new environmental skin (Case study, SUVA Insurance Company). With an increasing demand in retrofitting and reusing buildings rather than constructing new ones, retrofitting the existing building stock presents the largest potential for the incorporation of energy efficient measures. By understanding the basic characteristics of the existing building stock, we can begin to make assumptions as to how to implement necessary solutions.

The following sections presents a brief overview of the classification and range of the existing building stock as well as a methodology and strategy used to develop a structured process in the application of retrofitting an existing building. The application of this research will make it possible to determine an approach and test the hypothesis of the potential benefits of implementing double-skin façade retrofits as a means of enhancing high-rise commercial building thermal performance within Hawai`i's climate.

[61] Wigginton, Michael, and Harris, Jude. Intelligent Skins. (Italy: Elsevier, 2002), 3.

5.1. Development of the High-rise

High-rise architecture of the United States in the twentieth century demonstrates a wide diversity defining distinct classifications. As a result, the development of high-rise buildings can be traced roughly into five distinct phases. In the early 1940s before the advent of air conditioning and fluorescent light fixtures, the buildings form was controlled by the need for natural daylight and ventilation.[62] The building width had to be limited to ensure that light and air reached all parts of the building. With a building width of 55 to 60 ft., office space on either side of a double-loaded corridor was common. In order to create more leasable space within a rectilinear square block, floor plans focused around a central core with radiating wings. The building's façade was typically constructed with heavy masonry cladding which resulted in an enormous amount of dead load.

The second phase of high-rise building configuration resulted in the development of air conditioning and fluorescent lighting. This period of development was famously noted as the modern movement in architecture, stressing simplicity in façade treatment and simple cubic shapes. With the development of curtain walls, glass boxes with exposed structural steel and concrete structures began to dominate high-rise design. The curtain wall was stretched tightly over the skin as the building shot up to the sky in one regular prismatic shape.

The third phase of high-rise development was a result of the interaction between the architectural communities towards the highly repetitive nature of the boxes on cityscapes. The simplistic prismatic nature of the box has only four corners, and thus four corner offices. With an increasing demand for primer lease space, the trend in high-rise planning shifted to provide as many corner offices as possible. As a result, an undulating exterior form was established by providing niches, notches and other contortions at the perimeter of the building. In order to create visual identity, setbacks were established at intermediate levels. A simple plan shape is sliced to create vertical lines and emphasize the verticality of the building while simultaneously provide additional corner offices.

The fourth phase of high-rise office design known as the postmodern era brings forth a high level of articulation. These buildings not only have setbacks, angles, notches, and curves

[62] Taranath, Bungale S. "Structural Analysis and Design of Tall Buildings." (New York: McGraw-Hill Book Company, 1988) 16.

but use a hybrid of various structural systems. This articulation of the high-rise evolved within three major elements; the top of the building, the entrance to the building, and the search for identity. In the early phases of development, many high-rise buildings consisted of flat roofs, generated from a functional aspect. Since then, many buildings tops are a peaked roof, pyramidal, domed or a combination of these. In an attempt to give the building a street level identity, elaborate entrances to the building were created. With the continuous battle for personal identity within the cityscape, articulated development of the façade was used to pronounce the identity of the building. Terracing of building plans, cutouts, slicing, and overhangs were implemented throughout the height of the building.

The fifth phase can be seen as a modification of the current building shapes within the context of energy conservation. We are currently witnessing the development of buildings which respond to natural daylighting with courtyards, light wells, and skylights. Increasing energy conservation efforts have brought about an understanding of spaces as a whole, especially in relation as to how it affects occupant comfort. Instead of relying totally on mechanical heating and cooling systems and electrical lighting, designers are considering possible solar controls outside and in as an integral part of both engineering and architectural design.

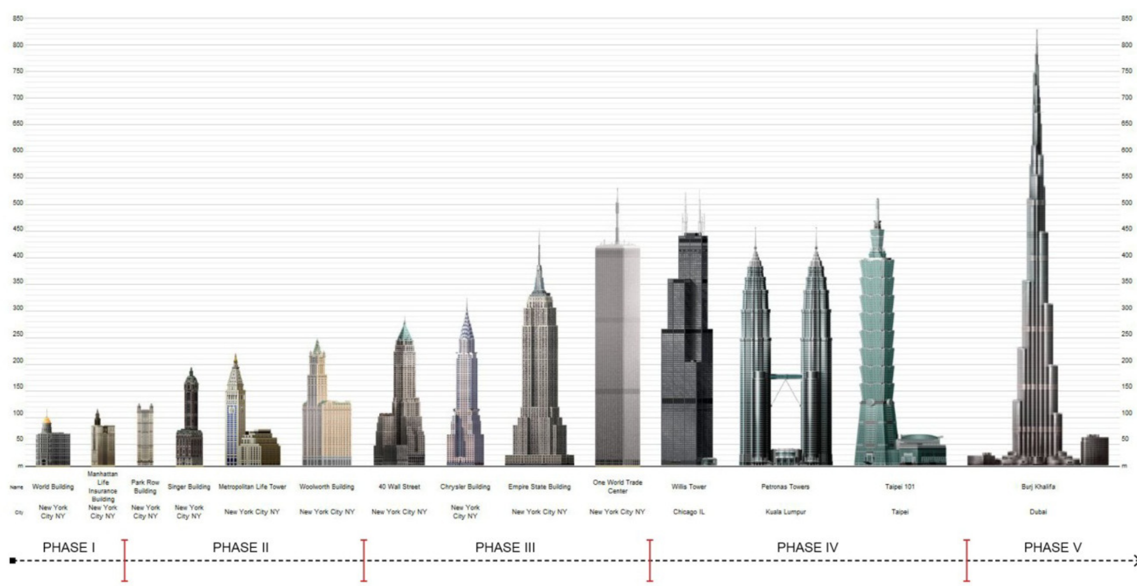
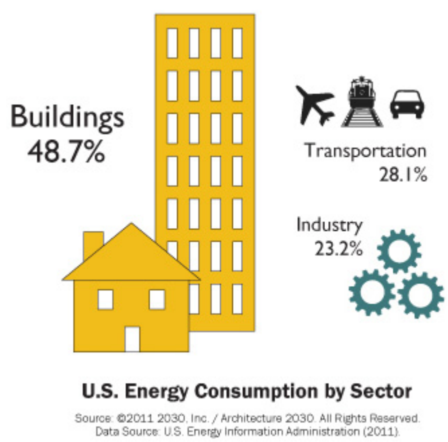


Fig. 5.1: Development of the high-rise through five phases.

The high-rise building development can be thought of as a progressive reduction of materials used within the space occupied by the building; a hollowing of the interior of the building. From a structural design consideration, a building can be considered tall when the effects of lateral loads are reflected in the design. A current trend in high-rise architecture is to have a free-form shape that fulfills the dual function of creating an incredible exterior and at the same time provide a highly desirable interior space.

5.2. Commercial Sector Energy Consumption

According to the U.S. Energy Information Administration (EIA), the Building Sector consumes nearly half (48.7%) of all energy produced in the United States and seventy-six percent (75.7%) of all the electricity produced in the U.S. is used just to operate buildings.[63] For the reason that buildings in the U.S. are the largest emitter of greenhouse gases and is the leading contributor to global climate change. In addition, EIA reports that annual electricity demands are increasing, attributing to this increase in energy consumption within the built environment.



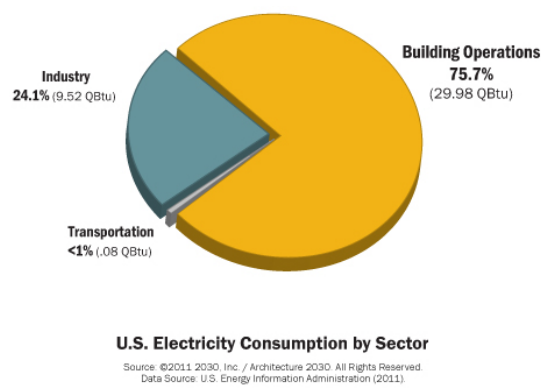


Fig. 5.2: U.S. Energy consumption by sector.

Commercial buildings represent about one-fifth of U.S. energy consumption, with office spaces representing the leader of energy consumption. The top three energy uses within the commercial sector is lighting and HVAC demands which contribute 75% of the buildings total energy consumption. The U.S. Department of Energy indicates that commercial buildings

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[63] Architecture 2030. "Why?" Accessed February 24, 2010.

consumed 17.9 quads of primary energy, resenting 46% of building energy consumption and 19% of the total U.S. energy consumption.

Hawai`i is isolated from the U.S. mainland and its energy consumption is unique among the other states as it depends entirely on imported fossil fuels to meet energy demand. Due to heavy jet fuel usage and the shipping industry, the transportation sector is the leading energy consuming sector and accounts for over one-half of the State's total energy consumption.[64] However, this should not undermine the importance of reducing energy load within the building stock. Within the building sector, office buildings stand out as a major energy consumer. With a large dependence on air conditioning systems continuously rising, an increase in energy consumption is evident. In a typical leeward Oahu office, nearly 43% of energy consumption is spent on cooling alone.

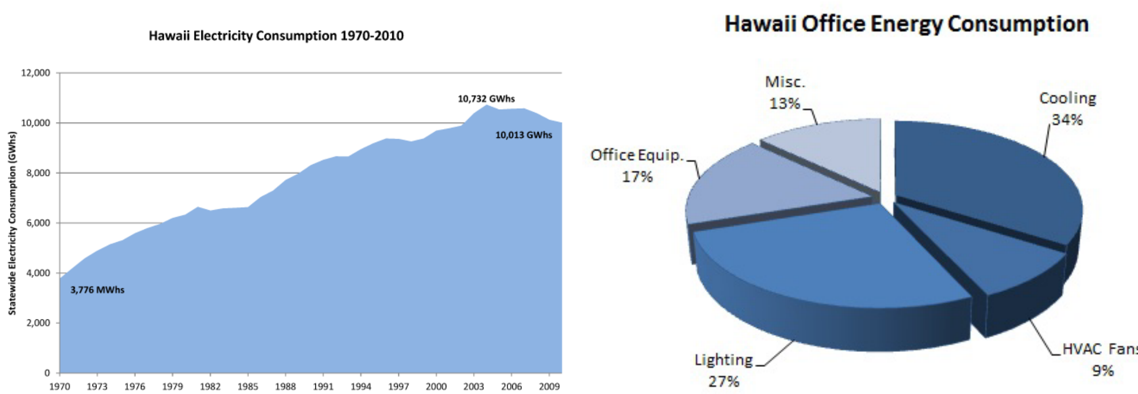


Fig. 5.3: Hawai`i's energy consumption.

The configuration of office building facades in Hawai`i's climate has a major impact on reducing/increasing the building's energy demand. In hot climates, the building façade is responsible for up to 45% of the cooling loads.[65] Contribution of the façade to building sensable loads include, window solar radiation, conduction and sensible ventilation gains. The dynamic relationship between the building façade assembly, age and type of building systems, occupant patterns and exposure to its micro-climate all influanace the patterns of energy consumption. In Hawai`i it is increasingly observed that existing commercial high-rise buildings with highly glazed

[64] U.S Energy Information Administration. "Hawaii" Accessed April 5, 2012.
[65] H. Elkadi, T. Wiltshire, S. Nahyan, "Energy management of building envelopes in hot climate, in: Conference Proceedings of Energy & Environment Development Conference" Port Elizabeth, South Africa,1999.

facades present overheating challenges due to high outside temperatures and solar gains. The increased need for air conditioning adopted to provide comfortable temperatures within work hours corresponds with the peak temperatures in the day.

5.3. Characteristics of Existing Commercial High-rise Buildings

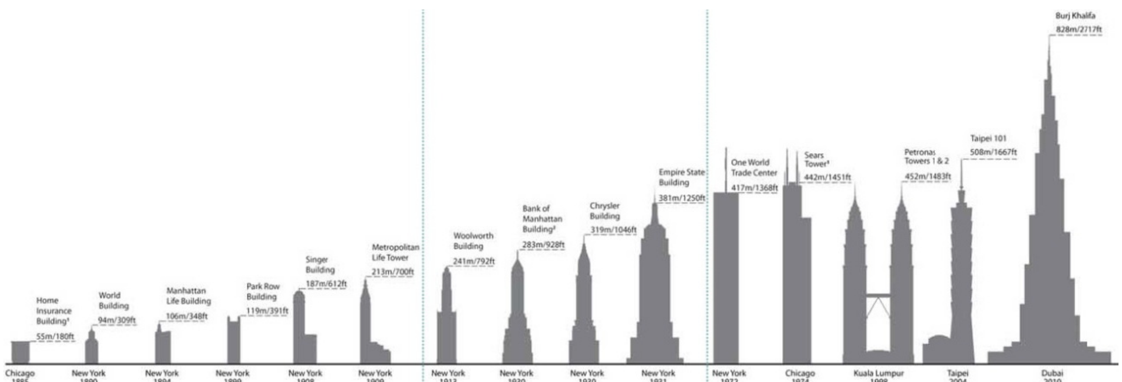
A literature search revealed that a typology to classify office buildings according to their characteristics that effect building facade performance has not been prepared previously. Thus, research has been conducted to identify and evaluate the building related and building independent properties which are relevant to a thermal performance concept. By profiling existing commercial high-rise buildings, it is possible to identify characteristics of the stock and evaluate the wide range of building features that affect performance conditions. Classification of the building stock helps to create an orderly arrangement of a large array of building elements so that their differences and similarities can be better understood and recognized.

The following analysis of the existing building stock characteristic such as building height, geometry, size of floor plate, lease span, window type and area, and façade system. By understanding the existing building stock and its characteristics, the potential of retrofitting a building's façade to enhance thermal performance can present favorable pre-conditions.

5.2.1. Height Criteria

There is no absolute definition of what constitutes a "tall building". It is a building that exhibits some elements of "tallness" in various categories. It's not just about height but about the context in which it exists. For example, a 15-story building may not be considered a tall building in a high-rise city such as New York, but in a suburb it may be distinctly taller. A tall building in not just about height but also about proportion. There are several high-rise buildings which are not particularly high, but are slender enough to give the appearance of a tall building, especially against low urban backgrounds. Consequently, classifying the height of a high-rise building is relative to their size/floor area and the context in which it exists.

In an attempt to establish a categorization for high-rise buildings in relation to the number of stories, the tallest buildings completed between 1961 and 2010 were studied. With the growing trend of tall buildings, the means of classifying building heights is considerably difficult. In general one can assume that the classification of a high-rise building is relative within its context. The overall height of a building can be classified into low-rise, mid-rise and high-rise.



5.2.2. Building Geometry

The geometry of tall buildings can range considerably but a recent survey of 115 high-rise buildings over 40-stories tall concluded that 28% were square, 47% were rectangular, 7% were circular and 5% were triangular.[66] However, building that were over 60 stories tall 30% were square and 25% were rectangular. This means that there is a tendency for the use of square floor plan when building height is increased.

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[66] Choi JS, "A study of form composition and efficiency in high-rise office buildings." Journal of the Architecture Institute of Korea 23(6): 33-40

In structural terms, square floor plans resist loads equally in all directions and are more economical than circular and triangular plans. Buildings with symmetrical plans are less susceptible to lateral wind loads than asymmetrical or curved shapes. This is particularly important in super tall building when designing fenestration systems as building movement could be problematic.

5.2.3. Size of Floor Plate

The size of the floor plate is largely determined by the occupants' requirements subject to various legal constraints. Legal regulations often state the permitted maximum site coverage which in effect limits the size of the floor plate in relation to its site area. Building codes also state the maximum distance for the farthest point to a protected exit. One of the major considerations behind the classification of floor plates is the lettable (rentable) to gross floor area ratio and the wall to floor area ratio.

The lettable to gross floor ratio depends on the size of the floor plate in relation to its service core location. The lettable to gross floor ratio of a building can be optimized by maximizing the floor plate area and minimizing the size of the service core to an acceptable level. The size of a floor plate in high-rise buildings range considerably however it is common for an office building to have a high lettable gross floor ratio of about 80%.

5.2.4. Lease Span

The lease span of a building is the clear distance from the service core to the external envelope. It is dependent on the functional requirements and size of the floor plate and is an important consideration for space planning. The lease span is conceptually provided by local codes, the functional requirements that impact the structure, as well as the accessibility of natural light and ventilation from the exterior of the building. As a result, the lease span plays an important impact on the environmental implications effecting building performance. When considering daylight, thermal and ventilation performance issues, the quality and quantity of performance will be determined by the lease span distance. According to the Council on Tall Buildings and Urban Habitat, the depth of the lease span should be between 33 and 46 ft. for office buildings.[67] According to resent research, 80% of high-rise buildings use a lease span of 35 to 50 ft.[68] A shallower lease span is preferred by occupants when focusing on interior environmental quality even though a longer lease span provides a more flexible interior. One can consider four types of lease spans when characterizing the depth of the space; very deep, deep, medium, and shallow. A very deep space span is classified as a space being over 66 ft., a deep space is 36-62 ft. deep, medium at 20-33 ft. and a shallow space at 13-16 ft. deep. Based on the lease span range data mentioned above, four office types with lease spans ranging from 13 to 66 ft. can be considered.

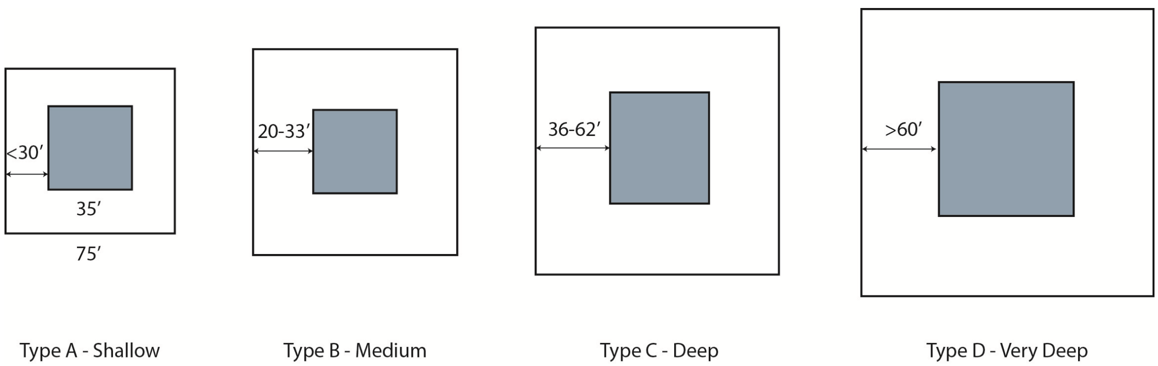


Fig. 5.6: Four office types by lease span.

5.2.5. Window Area and Type

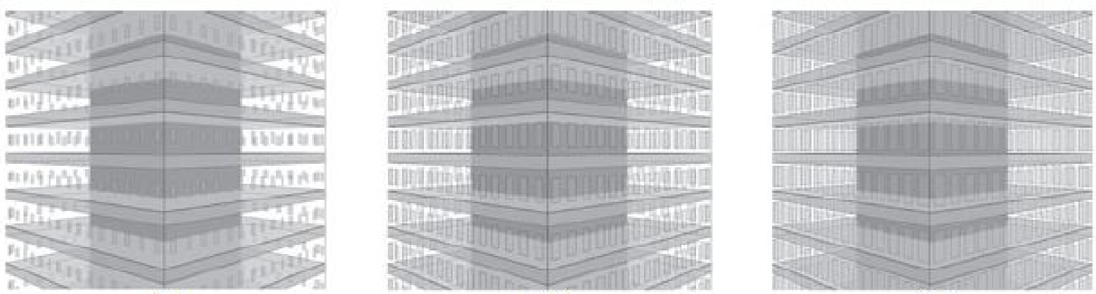
A buildings window system provides visual connections between the exterior and interior of the building but also carry important issues of managing heat gain and loss, as well as controlling natural daylighting from entering the building. As the heat gains through opaque walls are low due to the current high standard of thermal insulation required, it is the window-to-wall ratio and the combination of glazing types and sun shading system that effect the magnitude of the solar gains.

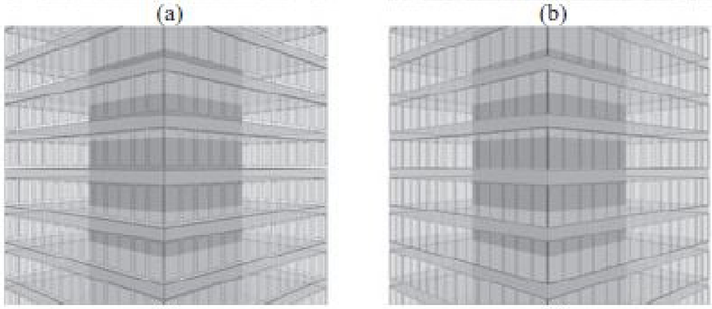
Window-to-wall ratios between 25 - 35% greatly reduce the amount of solar gains that enter the building but provide very little visual connection to the exterior. If windows are provided where views and natural daylighting are desirable, the overall window-to-wall ratio will

[67] CTBUH, “Architecture of Tall Buildings.” (Pennsylvania, McGraw-Hill, 1995).
[68] Choi JS, “A study of form composition and efficiency in high-rise office buildings.” Journal of the Architecture Institute of Korea 23(6): 33-40

range from 35-60% without having adverse effects on the quality of the space. With many existing high-rise buildings a completely glazed façade is often evident. With a window-to-wall ratio over 60%, solar heat gains and loss can become problematic and create an unfavorable condition. This results in an increased dependency on HVAC systems to preserve the indoor environments quality.

The two main factors that determine the amount of daylight and solar gains entering a building are the window size and type. These two factors are directly proportional to the indoor daylight and thermal performance factors. According to ASHRAE standard and IECC, the recommended window-to-wall ratio is 50% and the maximum 40% above-floor area. However, current trends in high-rise building facades are much higher with the application of fully glazed facades. As a result, the existing building stock of high-rise buildings window-to-wall ratio ranges considerably from 10-90%.





	WWR* (%)	WNWR* (%)
(a)	7%	10%
(b)	21%	30%
(c)	35%	50%
(d)	48%	70%
(e)	62%	90%

Fig. 5.7: Window configuration in percentage of glass

For the specified given window area, the glass type controls the amount of daylight that penetrates in terms of Visible Transmittance (VT). VT is the visible light through the glazing and determined the quality of light admission. The Solar Heat Gain Coefficient (SHGC) measures how well a window blocks heat from sunlight. The SHGC is a fraction of the heat from the sun that enters through a window expressed as a number between 1 and 0. The lower a windows SHGC, the less solar heat gain that is transmitted through the window. These two factors, along with the wall-to-window ratio all contribute to the environmental quality of the interior space. The application of different fenestration protection parameters has a direct impact on the effect of glazing area, VT and SHGC.

5.2.6. Façade Systems

Building envelopes are classified by their methods of fabrication and installation. Although there are many types of envelope systems, (i.e. punched window systems, ribbon window systems, curtain walls, etc.) solutions for building facades are driven by various factors; performance, cost, aesthetics, constructability, availability, etc. As with most building solutions, the variables are endless when it comes to identifying the right system. As a result, it is extremely important to understand the specific systems and the basics of their characteristics. Prior to the development of the glazed curtain wall, buildings comprised of high levels of thermal mass and a low percentage of façade transparency. The impact of the modern glazed curtain wall resulted in an increased façade transparency, reduction of envelope insulation and increased heat loss/gain. Early glazed curtain wall high-rise buildings were constructed of poor performance, single-glazed curtain wall with tinted glass and a high level of transparency. Modern curtain wall high-rise buildings implement a high-performance double-skin and triple glazed system with clear glass and a high level of façade transparency.

A comparative façade analysis of existing envelope systems will help categorize façade type for a given application. By developing a systematic evaluation of alternative fenestration systems for project-specific commercial building applications, effective analysis and synthesis of wall systems and investigates the performance and viability of products and systems. The results and findings can be presented in a series of detailed matrices that compare fenestration design scenarios to help provide the knowledge used to solve design problems useful in addressing needs of a particular situation.

	STICK SYSTEMS	UNITIZED SYSTEMS	WINDOW WALL SYSTEMS	RIBBON WINDOW SYSTEMS	PUNCHED WINDOW SYSTEMS
AESTHETICS	GRID WITH EXPOSED METAL MULLIONS	TYP. ALL GLASS WITH MONOLITHIC APPEARANCE, MAXIMUM TRANSPARENCY	UNITIZED GRID LIKE APPEARANCE WITH SEPARATE SPANDREL CONDITION	HORIZONTAL "RIBBON" WINDOW AND SPANDREL PATTERN	BOX WINDOW PROVIDES ORDERED FACADE PATTERN
TECHNICAL	INDIVIDUAL PARTS ASSEMBLED ON SITE	UNITIZED SYSTEM AND ASSEMBLY METHOD	UNITIZED SYSTEM SITS ON SLAB WITH SPANDREL CONDITION	PREASSEMBLED WINDOW INSERTS	WINDOW INSERTS PLACED INTO EXISTING ENVELOPE
TYPICAL INSTALLATION	LOW MIDRISE HIGHRISE	MIDRISE HIGHRISE	LOW MIDRISE	LOW MIDRISE	LOW MIDRISE HIGHRISE
ANALYSIS	CUSTOMIZATION WITH RANGE OF COMPONENTS	UNLIMITED CUSTOMIZATION ENGINEERED SYSTEM IMPROVES BUILDING PERFORMANCE	MODERATE CUSTOMIZATION SPANDREL CONDITION DETAILED	MINIMAL CUSTOMIZATION	STANDARDIZED BOX WINDOWS WITH LITTLE CUSTOMIZATION
COST	$$$	$$$$	$$	$$	$

Fig. 5.8: Comparative façade analysis.

This search for typical characteristics of the existing building stock and their level of influence on thermal comfort has revealed specific building classifications. With an evaluation of these characteristics common in commercial high-rise buildings one can begin to rank categories which are relevant to a thermal comfort concept. Identifying those characteristics which are shared throughout the building stock will help to recognize typical design conditions which can be applicable across the entire building stock.

One of the foremost characteristics that influence thermal comfort in high-rise buildings is the window type and area category. The window to wall ratio determines the percent of glazing used on the envelope of a building. It is evident that a large portion of the existing building stock utilizes a relatively high window to wall ratio with their fully glazed curtain wall facades. With this type of condition, the thermal performance of the building becomes a function of the glazing, frame, spandrel condition and edge details. The flow of heat through a wall, both inward and outward, is determined by the resistance of the materials in the wall assembly. The overall U-value of the building envelope is the result of the complex relationships between the values of individual components and their materiality.

Due to the fact that the window type and area of a building characteristic is one of the most important factors in determining the total solar energy entering the building at any given time it is relative to identify these elements within the study. The amount of solar energy entering a building through the façade is determined by the solar transmittance through the glazing and the shading factor of the solar screening as well as the conductive and radiant control of the assembly. In many buildings today, the use of solar control can be seen in the implementation of shading devices and material specifications. These methods of enhancing thermal control will be explored through the design and analysis of the selected building. In an effort to enhance thermal performance of an existing façade assembly, attention will be placed on identifying a wall type that is common and relevant to the existing building stock.

5.4. Retrofitting Strategies

As with every construction, office buildings are subject to physical and functional decline. Regular building maintenance can slow down this process, but after a certain time larger interventions become inevitable. The life duration of the elements of a building varies considerably. In office buildings, interior retrofits can occur within several months whereas façade retrofits may occur within several years. The necessity of an intervention on the façade is generally determined by the conditions of the existing building as well as the project itself.

In order to structure an approach to this process, it is necessary to use a comprehensive retrofitting strategy. This strategy can simply be defined as a set of interventions, expressed by a clear architectural solution, through a full reinvention on the facade surfaces. Observation of specific retrofitting projects has shown that in the case of office building renovations the intervention on the original façade is particularly important in enhancing building performance. It is also evident that three main types of strategy can be identified:[69]

- *The Stabilization Strategy*: which consists of a set of interventions that do not fundamentally modify either the substance or the appearance of the building

[69] Rey, Emmanuel. "Office building retrofitting: multicriteria approach of an architectural and technical issue." Energy and Buildings 36 (2004): 367 – 372.

- *The Substitution Strategy*: which consists of a complete change of certain elements and transforms simultaneously the substance and the appearance of the building

- *The Double-skin Façade Strategy*: which consists of partially stabilizing the existing façade and adding a new glass skin. This strategy involves a complete metamorphosis of the building's appearance, but maintains a large portion of the original substance. As noted there are several types of double-skin façades.

As with their level of impact, the different strategies reveal considerable variations in terms of their performance. Thus, specific methodologies must be developed in the project as to take into consideration the various means of defining a building retrofit solution; building performance evaluation, energy audit, design solution, and implementation.

Building Performance Evaluation:

Building performance analysis to determine building candidacy for a retrofit solution. (Current energy usage and cost analysis, benchmark building against comparable buildings, potential energy and cost savings estimate, and recommended project approaches.)

Energy Audit:

A comprehensive and detailed study of your building's current energy use. All aspects of energy use are analyzed including equipment, usage patterns, maintenance and operations, historical data, building design, etc.; (Operations and equipment assessment, identify all potential energy reduction measures, retrofit project analysis.)

Design Solution:

Using the results of the energy audit one can design the most appropriate building retrofit solution; one which reaches project goals, maximizes building performance, and minimizes energy usage. Energy modeling will be used to determine the most effective solution along with many other considerations. (Define project goals and solution, energy modeling to determine appropriate solution.)

Implementation:

Implementation of the designed building retrofit solution. Validate that the retrofit achieved the project goals, and ensure the building will perform to specific standards. An updated building energy audit will be conducted as it will be used to compare against the old building analysis.

Office building retrofitting strategies are influenced by various parameters. Beyond the influence of providing optimal thermal performance, other important factors will help to influence the final building retrofit solution. With a double-skin retrofit solution the design can modify various preferences driven by performance evaluation, referring to user comfort requirements and retrofitting considerations. Other elements related to the building's use will have an important role in the design of the most suitable solution. In relation to enhancing building performance, an environmental skin can offer an innovative alternative.

III. PROJECT INVESTIGATION

1. BUILDING & ENVIRONMENT

The preceding research has recognized that a new era of sustainable buildings has come to reality; an era of innovation where dynamic, intelligent systems can have a greater impact on buildings and its occupants than those operating independently. What if we could redesign buildings that have the ability to respond to the environment around them? How can a building's façade act as an active element of environmental control? These questions can be answered as designers are now creating what has been labeled as the "intelligent environmental skin".

This research has focused on identifying what it means for a building's façade to be labeled as "intelligent" and has recognizing specific intelligent features which make up the genetic DNA of its assembly. Due to the fact that the fundamental role of buildings is to protect its occupants from external climactic conditions, developing an appropriate building envelope is an important part of enhancing a building overall thermal performance. Focus is placed on the role of the façade as its plays an important part through which these conditions can be controlled. An intelligent environmental skin, an element which performs in respond to environmental variations can be utilized to optimize the performance capacity of an existing building. In a context of an increasing number of retrofitting projects and greater consideration for sustainability, designers are looking at the optimization of the existing building stock. Exploration of this growing trend had identified similar characteristics which are shared throughout the building stock and has helped to recognize typical typological conditions.

This research has aimed at identifying strategies for optimizing the thermal performance of existing buildings through the implementation of a double-skin façade system. With this understanding, the application of this investigation will follow with design simulations focusing on re-skinning the First Hawai`ian Center in downtown Honolulu with a double-skin facade. The project will focus on testing various high-performance façade scenarios. By exploring new ways to define the façade of buildings, one has the ability to challenge existing standards and produce a valid solution in the retrofit of existing building facades; an environmental skin capable of providing improved thermal performance in response to its external environmental conditions.

1.1. The First Hawai`ian Center

The First Hawai`ian Center, located at 999 Bishop Street in downtown Honolulu, is the tallest building in Hawai`i and the corporate headquarters of First Hawai`ian Bank. Completed in 1996, the First Hawai`ian Center is 430 feet tall, 30 stories and has over 645,000 square feet of space. Designed by the architectural firm Kohn Pederson Fox Associates (KPF), the tower is composed of two distinct forms, one which faces the sea and the other which faces the mountains. It is linked to the ground by a low podium which houses The Contemporary Museum and a banking hall. This podium engages the tower with the urban context and shapes a series of gardens along the surrounding streets.

The building's fenestration recognizes each of its major parts: horizontally louvered windows frame views of the sea and the horizon; vertically proportioned openings face the mountains; and the podium is dominated by a great wall of prismatic-glass louvers. These louvers fracture the light passing through them into a dazzling spectral brilliance. This kaleidoscopic display of natural light continually transforms the interior of the museum and the banking hall.

Technical details:

Height: 429 ft.

Floor Area: 645,834 sq. ft.

Floor Count: 30

Structure: Steel Frame

Façade Material: Glass

Façade System: Curtain Wall

Architectural Style: Post-Modern

Building Cost: $95 Million

Fig. 1.1: First Hawaiian Center, Downtown Honolulu.

1.2. Climate as Context

If a building is designed and constructed to accommodate the local climate (i.e. by using appropriate building components and operation strategies), then the achievement of occupant comfort and efficient operation in the building will be greatly increased. By further categorizing these principles of climate related issues, specific information about environmental conditions such as common air temperature ranges, humidity, wind and precipitation can be identified.

The warm-humid climate of Hawai`i is a combination of various kinds of weather. The significant features of Hawai`i's climate include warm air temperatures throughout the year, moderate humidity, prevailing northeasterly trade winds, significant differences in rainfall within short distances, and infrequent severe storms. Hawai`i is in the tropics, where the length of day and temperature are relatively uniform throughout the year. Uniform day lengths result in small seasonal variations in incoming solar radiation and, therefore, temperature. Generally, the major challenge to maintaining thermally comfortable conditions is the overheated, humid natural environment.

Hawai`i's terrain significantly influences every aspect of its weather and climate. The variation of mountains, valleys and ridges gives Hawai`i a climate that is different from the surrounding ocean as well as the other islands. The mountains obstruct, deflect and accelerate the flow of air. When warm, moist air rises over windward coasts and slopes, clouds and rainfall are much greater than over the open sea. Leeward areas, where the air descends, tend to be sunny and dry. In places sheltered by terrain, local air movements are significantly different from winds in exposed areas.

In order to understand how these environmental systems affect the existing conditions of the building, several environmental analysis simulations must be completed. By establishing the base case scenario for the building and its context, one can begin to analyze and experiment with several design iterations and measure their impact on thermal performance. The following section begins to identify the existing environment conditions that affect the existing state of the building. These include, monthly diurnal averages, solar exposure modeling, air movement and velocity studies. By evaluating the existing environmental conditions one can begin to identify specific challenges and opportunities then evaluate the results to help inform the design process. The primary nature of establishing this base case scenario is to help identify which areas of this study are imperative as well as provide a comparative analysis between the final designs with the existing building condition.

1.2.1. Comfort

Monthly Diurnal Averages

The monthly diurnal chart illustrates average daily fluctuations of temperature and the incident radiation for each month per hour. Following the blue air temperature line, one can see that the temperature is lower at night and rises during the day. The red band represents the minimum, maximum, and average outdoor temperature for each month per hour. The green thermal comfort band indicates the temperatures at which people are comfortable. This is also the comfort range to which indoor temperatures are designed. When the red temperature band falls entirely below the comfort band, there is likely excessive heat dissipation, indicating a need for heating. When it rises above the comfort band, there is potentially inadequate heat dissipation, meaning inhabitants will feel too hot and there is a need for cooling.

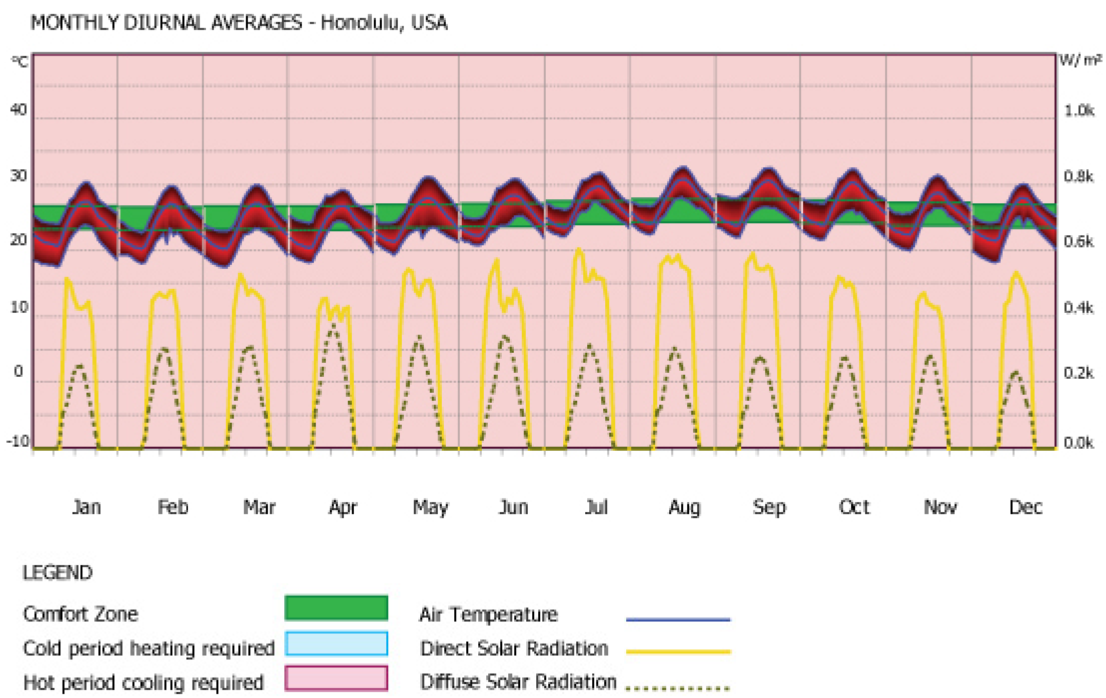


Fig. 1.2: Monthly diurnal averages for Honolulu, Hawai`i.

Psychrometric Chart

The psychrometric chart determines the appropriate climatic response that determines thermal comfort in a particular climate. It shows the relationship of the four climate variables that determine human comfort. By plotting temperature and relative humidity, one can determine if the resulting condition is comfortable (within the comfort zone). The chart illustrates hourly data, plotted as points, to indicate the frequency of temperatures for Hawai`i's climate. The temperature in Celsius is shown along the X axis and the Absolute Humidity, as a percentage, along the Y axis. The yellow outline shows the comfort zone for occupants. This should also be the comfort range to which indoor temperatures are designed. Using the design strategies indicated on the chart, one can extend the comfort zone throughout the year, as shown by the corresponding colored outlines.

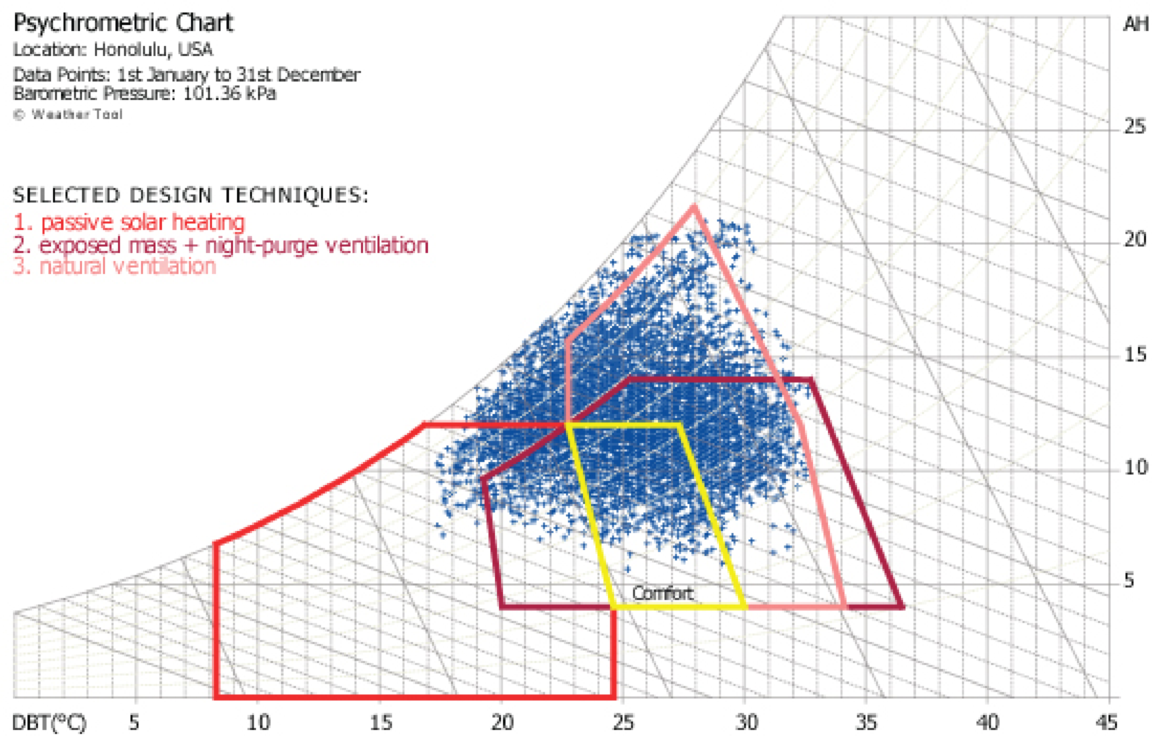


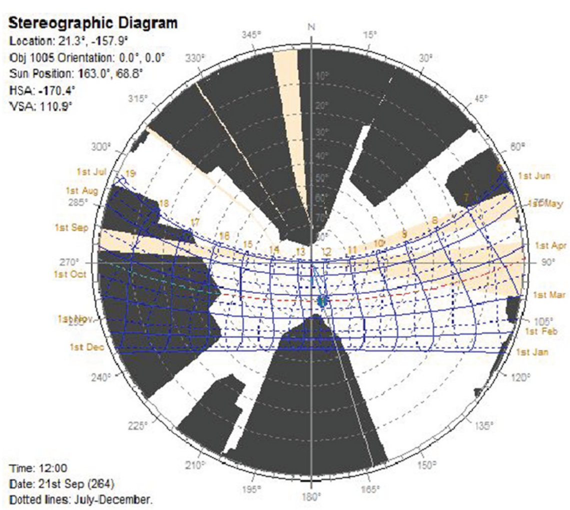
Fig. 1.3: Psychrometric chart for Honolulu.

Several types of information can be gathered from a yearly plot. The psychrometric chart for Honolulu, Hawai`i indicates that majority of the plots are above the comfort zone and can be offset by natural ventilation. The amount of natural ventilation and availability of wind can be estimated by CFD analysis. It is important to remember that these plots represent outdoor conditions and that a building has the potential to control its internal microclimate.

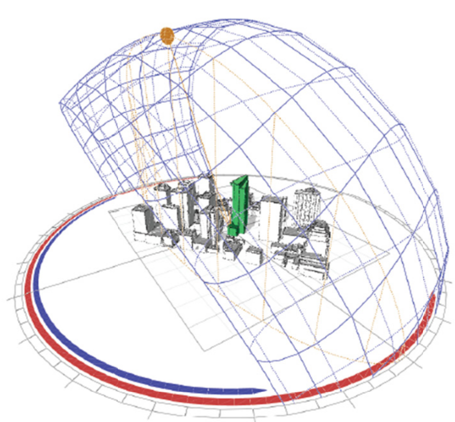
1.2.1. Solar Exposure

Sun Path Diagram

The sun path diagram, with existing site objects can be used to determine the times of the day and year in which the sun will be available on the site. Starting with the existing building conditions, we can compare solar exposure and availability on each façade of the building. The Sun Path plan diagram shows the annual and daily sun path for given coordinates. The highlighted path is September 21st, which corresponds to the autumnal equinox and represents the average sun path. The orange sphere shows the location of the sun. The solid blue lines show the daily path of the sun during the first half of the year, while the dotted blue lines show its path the remaining 6 months. The blue figure eight lines indicate the sun's location at a given hour throughout the year. The solar altitude angle (α) at which the sun's rays strike the buildings surface is the measurement between the horizon and the position of the sun above the horizon shown as concentric circles. Solar bearing angle (β) (or azimuth angle) is measured from the north-south axis to the vertical plane in the sun represented with the degrees around the outer circle.



Sun Path Diagram



3D Sun Path

Figure 1.4: Sun path diagram with plot of site obstructions at 100’ elevation.

The same diagram of altitudes and azimuths is also used to describe the position and size of objects from a particular point on the site. Adjacent buildings can be described in terms of their altitude and azimuth from that point. By plotting them on the sun path diagram, one can tell when they will obstruct the sun and therefore shade the building. Shading by these buildings is beneficial to reduce overheating.

Incident Solar Radiation

The solar radiation passing through a window assembly can cause considerable thermal discomfort for occupants if not controlled. Incident solar radiation (insolation) is the amount of energy striking a surface per unit of time and area (Wh/m^2). The material upon which it strikes determines the amount of solar radiation absorbed and/or transmitted by the surface. The total insolation ($G_{incident}$) is affected by:[70]

- The angle of incidence of the solar radiation (A)
- The current shading fraction of the surface by surrounding geometry (F_{shad})
- The fraction of diffuse sky radiation actually visible from the surface (F_{sky})

These factors affect the direct (G_{direct}) and diffuse sky ($G_{diffuse}$) radiation components. Direct beam solar radiation is a component of solar radiation that is not scattered by the atmosphere (i.e. contrast to diffused solar radiation which is scattered by the atmosphere). The direct-beam and diffuse components comprise the total (global) solar radiation. On clear sky days, the direct beam solar radiation will be substantial more intense than the diffuse component. For such days it is important for the design to provide means for shading the interiors of the building. Otherwise, the interiors of these buildings may be substantially overheated by the transmission of direct beam radiation through the fenestration assemblies. This depends on the material properties of that specific surface. Absorbed solar radiation ($G_{absorbed}$) is affected by that solar absorption value of a material (F_{abs}), its transparency value (F_{trans}) as well as their shading coefficient (SC). Direct sunlight from windows can account for over half of the summer cooling energy load in an air conditioned building. Transmission of direct beam solar radiation can also

[70] Natural Frequency, "Incident Solar Radiation", Accessed February 21, 2012. http://andrew-marsh.com/wiki/Incident_Solar_Radiation

present discomforting visual effect for building occupants. In response, a buildings envelope should prevent heat build-up while still maintaining a connection to the outdoors and access to natural light.

The following simulations have been performed to determine the cumulative yearly value of solar radiation that strikes the buildings envelope of a given orientation, in this case, north, east, south, west.

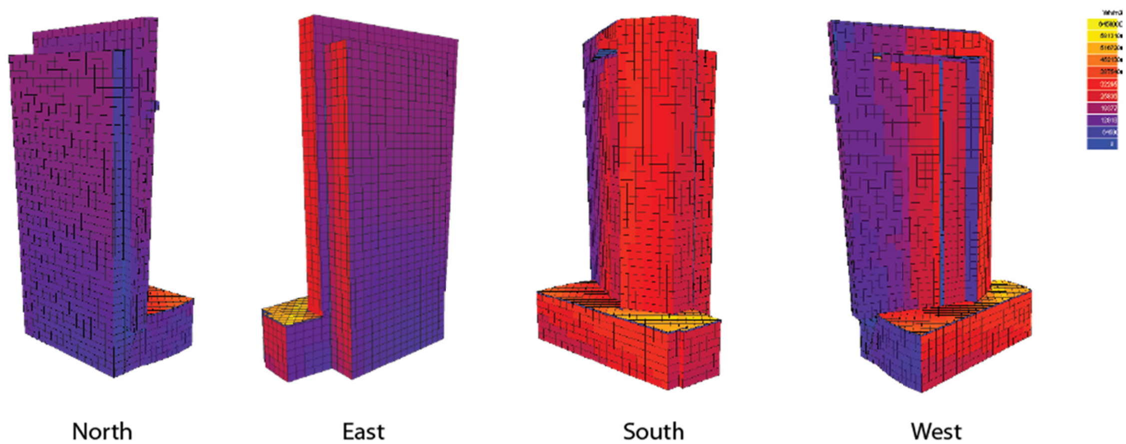


Fig. 1.5: Incident solar radiation analysis on the envelope of the Fist Hawai`ian Center.

Given the dynamic path of the sun through the sky and changes in contextual conditions, incident solar radiation varies over time as well as spatially across the façade of the building. Solar access refers to the availability of incident solar radiation (insolation), on surfaces and points of the building. The following solar access calculations are a cumulative yearly value between the hours of 8:00am to 6:00pm and determine the total radiation ($G_{incident}$) falling upon the façade of the building in Wh/m^2. The brighter the color, the higher the amount of radiation that is striking that particular surface. A brief evaluation of the existing conditions of the building shows that the south facing façade (which has the most solar exposure) has a high total radiation value and thus will be the most vulnerable surface to solar heat gains. However, due to the buildings orientation relative to cardinal points, each surface of the buildings envelope receives a wide range of exposure. On the north face of the building, there is very little solar exposure and results in a low amount of insolation that strikes this side of the building. The east facing side of the building is exposed to solar radiation during the morning hours of the day and results in moderate values. The west side of the building is exposed to the afternoon hours and also shows results of moderate radiation values although the values increase as the surface begins to face south-west.

These next simulations help determine the time of day during each month when solar radiation is useful and when it causes excessive heat gain. These amounts are given as monthly averages per hour. The hour changes along the Y axis and the month along the X axis. Different strategies can be devised to alleviate the effects of excessive radiation from various shading techniques to passive solar heating methods.

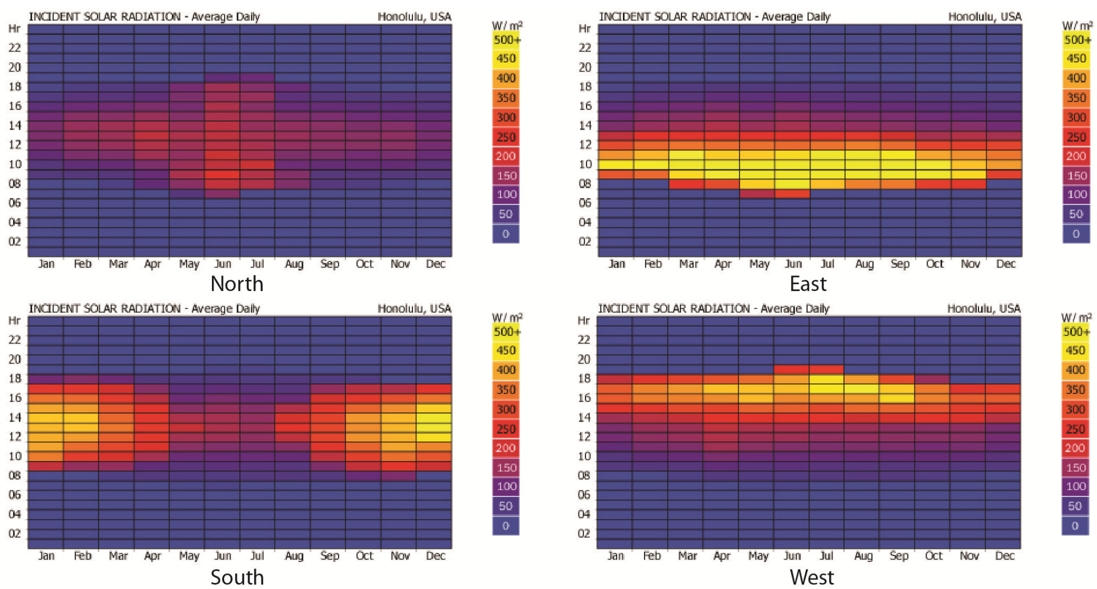


Fig. 1.6: Average monthly solar exposure.

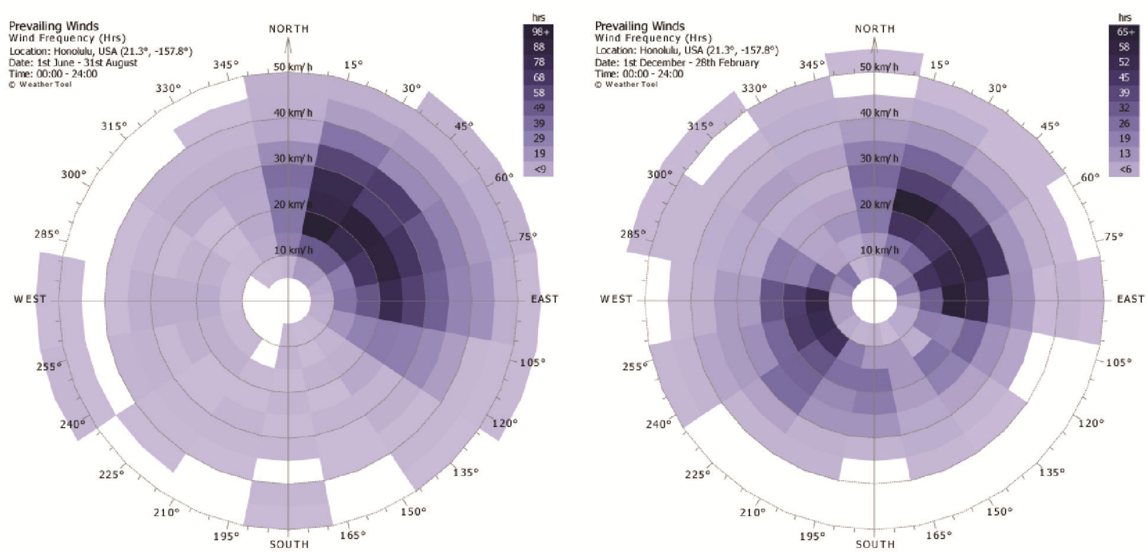
These radiation simulations help to determine which part of the buildings envelope receives the most solar radiation and which sections of the façade should be under evaluation. By determining which section of the building envelope is exposed to the highest level of solar radiation, the design project can focus on that particular area which would receive the most benefit and attempt to generalize the results upon the entire envelope of the building. Once the amount of incident solar radiation on a surface has been calculated, it is possible to determine how much of that radiation is absorbed or transmitted through the surface with a detailed study of the fenestration assembly.

1.2.3. Wind

Wind Rose

Hawai`i benefits from steady, gentle trade winds typically moving at 15 to 20 mph from the north-east to the south-west. These winds are steady throughout much of the year and tend to be stronger in the afternoon rather than at night. Southerly winds occur with regularly during the winter months as winter storms can bring in heavy winds and rains.

A wind rose can be used to characterize the direction, speed, and frequency of wind. It gives detailed information about wind direction and frequency for a month or a whole year. The wind rose is divided into sixteen pie-shaped sectors in which the frequency (hours) of wind is shown for summer and winter. The concentric circles indicate the wind speed (km/h). The degrees around the outer circle provide the azimuth of the wind, or the direction from which the wind blows. The semiannual wind rose for Honolulu, Hawai`i indicates that the wind comes predominantly from the north-east with greatest frequencies in the 20 to 30 km/h range. The wind rose during the winter months reveal that south-west winds also occur regularly.



Summer Winter

Fig. 1.7: Wind rose for Honolulu, Hawai`i during the summer and winter months.

Wind Flow

It is important to note that wind data are usually collected at airports and the wind speed and direction on the building's site may be quite different. Thus, it is important to understand the micro conditions of the site itself. A study of wind speed variation with height can be used to estimate the difference between wind speed measured at the airport and the conditions of the site. The wind flow patterns for a particular site can be understood in relation to airport data by simulating the way the site modifies the wind using Computational Fluid Dynamics (CFD) analysis. With these simulations we can begin to predict wind direction and speed by understanding the principles that govern air movement and thus become familiar with the way wind interacts with the buildings form. The following CFD simulations help to understand the specific effects of the buildings context on wind velocity.

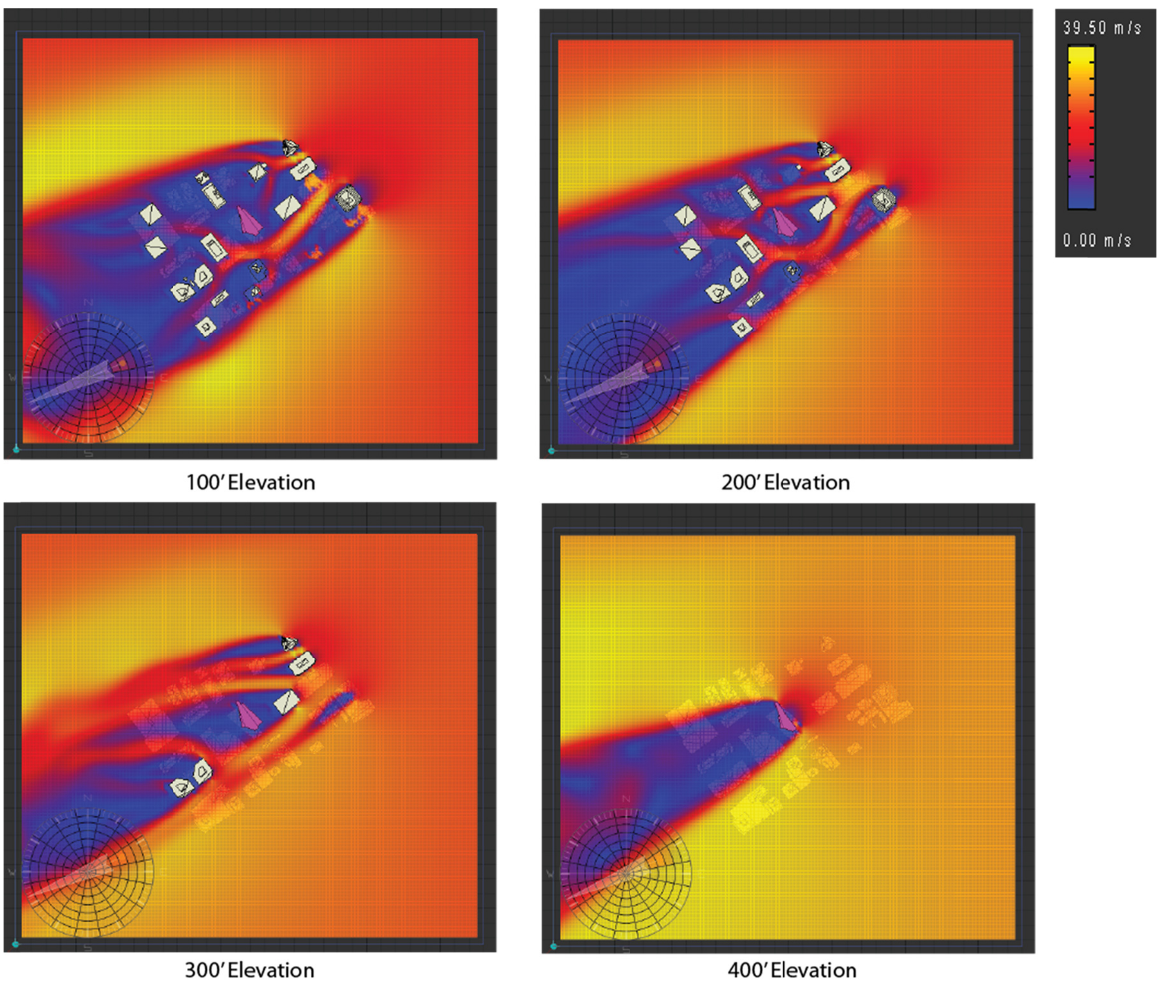


Fig. 1.8: CFD Analysis of the building within its context set of plan diagrams.

Wind patterns and velocity are altered by their interaction with built forms in complex ways. The resulting simulation of wind flow around buildings represents wind speed and direction. The bright colors of yellow and red indicate a higher velocity than colors of purple and blue. The low-pressure eddy zones have decreased wind speeds and are sometime termed as “wind shadows”. In most cases, high pressure occurs on the windward side and low pressure on the leeward side, while wind constricted as it moves through a gap between buildings it increases in velocity due to the Venturi effect. The upper set of plan diagrams show the impact of the buildings with and height and orientation of the site. At first one notices that depending on the elevation of the simulation the air velocity is slower near the ground surface than higher in altitude. This reduction in velocity is a function of an increase in pressure caused by the built context. Wind velocities measured at the site near the ground are frequently lower due to the wind diverted by buildings which increase turbulence and decrease velocity due to the obstructions. In contrast, with a higher elevation there are fewer obstructions and the exposed buildings experience relatively higher wind velocities.

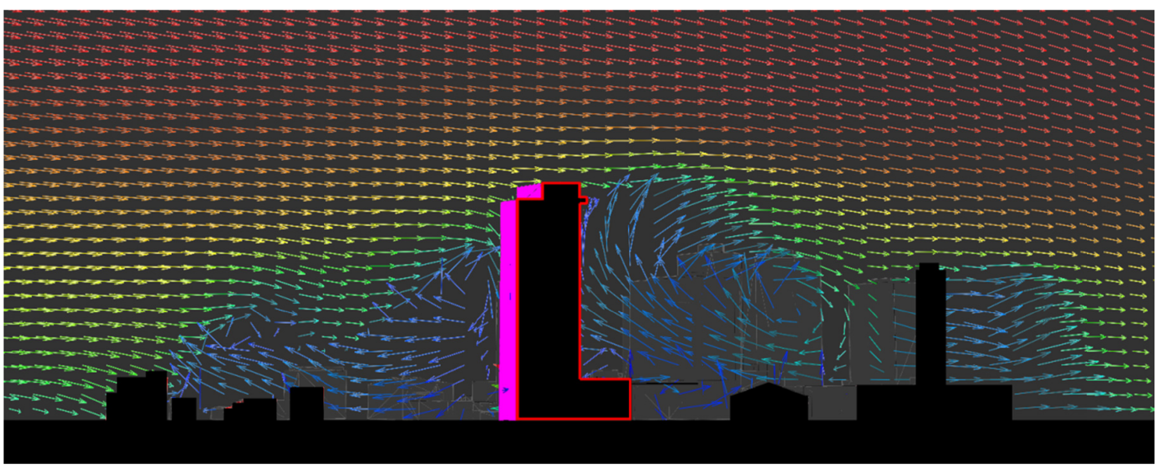


Fig. 1.9: North-south sectional CFD analysis of the building within its context.

The sectional diagram shows the impact of the buildings height on wind flow. The steep faces of the building deflect wind higher, extending the height and length of the low-pressure zone on the leeward side of the building. With an increase in the building height show similar patterns above the building, while the length of the wind shadow increases proportional to the buildings height. At the back of the building, air accelerated around the building continue its path, thus a negative pressure occurs behind the building. As a result, eddies spin up the side of the onrushing airstream. These eddies fill the leeward space with air. It is for this reason that the leeward side of the building is more turbulent.

By understanding the direction, velocity and principles of wind flow, one can begin to identify possible benefits that help promote the use of natural ventilation. Using the prevailing winds of the site, the building can implement a ventilation strategy which allows for cross ventilation of external air to enter through the north-east façade. The façade of the building can thus have the ability to control wind speeds throughout the office through the use of internal self-adjustments. Due to the steep faces of the buildings height, the eddy zone creates an updraft which could also be exploited. Since we know that the south side of the building will receive a high amount of solar heat gain, the building façade can take advantage of this and allow convection to wick away surface heat. By using these basic wind patterns, it is possible to fit basic design alternatives to respond to the climate and the buildings need for blocking or admitting wind. With this analysis it is possible to consider the impact of the building's façade in relation to wind patterns by creating different configurations and orientations to promote the substantial benefits of the existing wind patterns of the site.

1.2.4. Light

Solar Rays

A simulation focusing on the solar rays that will directly strike the building throughout the year helps to determine specific existing conditions that affect the buildings overall performance. The position of the sun varies according to the latitude, season and time of day and will have a significant impact on design decisions. During the winter solstice, December 21, the sun is at its most southernmost point in the sky where at noon it is at the lowest solar altitude angle above the horizon (45^0). Due to the fact that the south facing facades of the building are highly exposed, this condition causes considerable problems for the building as the low solar angle of the sun's rays creates excessive amounts of glare and heat gain to enter due to direct sunlight exposure. During the summer solstice, June 21, where the sun is at its northernmost position in the sky, at noon it is at the highest solar altitude angle (91^0). The diagram shows that during this time of the year the high angle prevents direct solar rays from striking the façade but with an increase in solar exposure on the roof surfaces of the building. During the equinox, which happens twice a year, the suns altitude angle is at the midpoint between solstices and represents the average sun path. With a proper understanding of solar availability of the building, one can begin to implement design strategies that utilize these environmental conditions as an advantage to promote energy-efficient and aesthetically pleasing solutions. However, if not carefully understood the building may overheat, be too bright, or have poor distribution of light. Excessive heat gain is also common problem associated with solar exposure that needs to be mitigated.

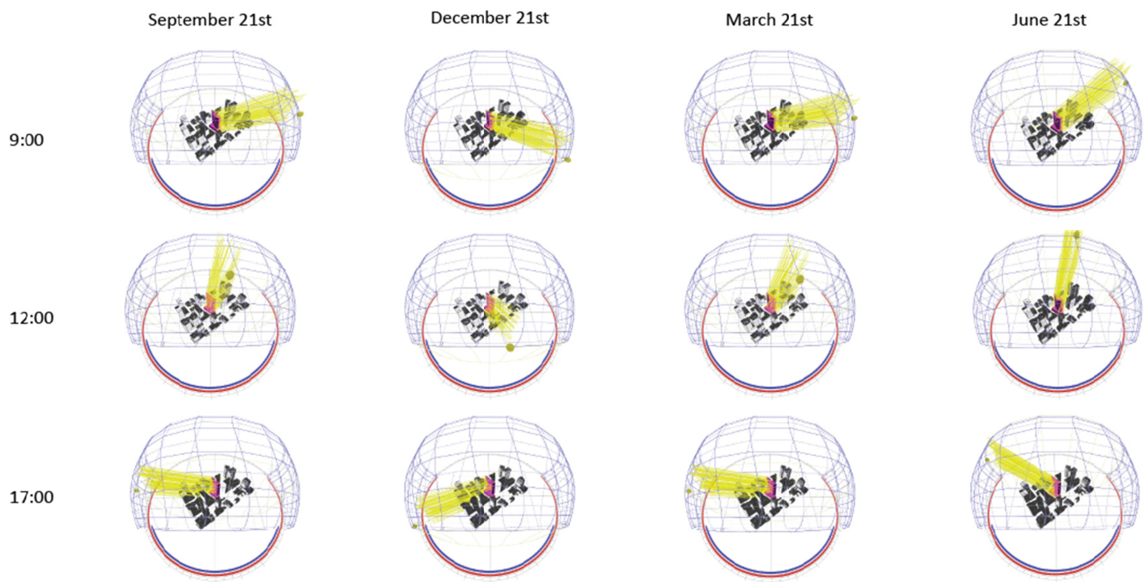


Fig. 1.10: Solar ray analysis on the envelope of the First Hawai`ian Center.

With an understanding of the basics, a detailed solar path analysis of solar rays that will impact the First Hawai`ian Center helps to inform schematic design decisions. The amount and intensity of solar rays that hit the façade of the building throughout the year play a major role in determining the amount of solar access and exposure the building will endure. It is important to note that surfaces that receive a high level of direct solar exposure will in return have ample amounts of daylighting opportunities as well as large amount of solar heat gains. Thus, it is important to understand the complexities of solar angles when determining specific design decisions. Environmental impact analysis on the solar exposure of the building helps to determine the amount of solar rays that will hit specific areas of the façade and inform the design by allowing decisions to be made early in the design process.

2. FORM AND ENVELOPE

The building itself is the basic factor that influences environmental performance. Its shape and construction greatly influence how much of the climate and internal loads are actually translated into heating and cooling requirements. Because the building is located in a sunny, hot climate it experiences a tremendous load from the sun per unit area of surface. However, the building envelope should be designed so that it reduces the area exposure to sun, provide shading for glazed surfaces, and be well insulated. With the proper design of fenestration assemblies much of that solar load can be prevented from increasing the cooling requirements. Like the techniques used in the previous section, they can be primarily directed at supplying specific information on the environmental patterns of the buildings envelope.
A variety of technical solutions can be used to produce a high-performance façade based on fundamental building concepts for solar heat gain control, daylighting, and ventilation. The following descriptions of the various fundamental concepts describe various environmental systems which affect the buildings energy-efficiency. In isolation, we can begin to understand the basics and the realization of a single given strategy (i.e. solar radiation), but one must begin to acknowledge that a combination of strategies (daylighting, solar control, and ventilation) one can achieve a higher level of integrated systems.

The following section focuses on these three fundamental concepts of solar control, daylighting and ventilation in a cooling-load dominated commercial building. For this building type and climate, window solar radiation and conduction heat gains contribute to total energy use consumption, increasing peak demands. Daylighting the perimeter zones are also critical where sunlight is abundant. Carefully identifying the existing condition will help to recognize areas which can be improved to increase occupancy comfort.

2.1. Façade Model

To begin to understand these specific areas of the building one must run through the process of first isolating those areas of interest. The building has to be simplified in order to obtain a simulation model. In the case for such a large building with many similar wall types, a small portion of the building's façade has been chosen. Further examination regarding the existing environmental characteristics requires analysis to further identify issues that are potentially critical. A model of three different levels is needed for reliable simulation of the thermal behavior of the façade and has been selected for modeling and as an appropriate boundary condition. The study focuses on the south-east facing highly glazed curtain wall which is particularly susceptible to high solar gain.

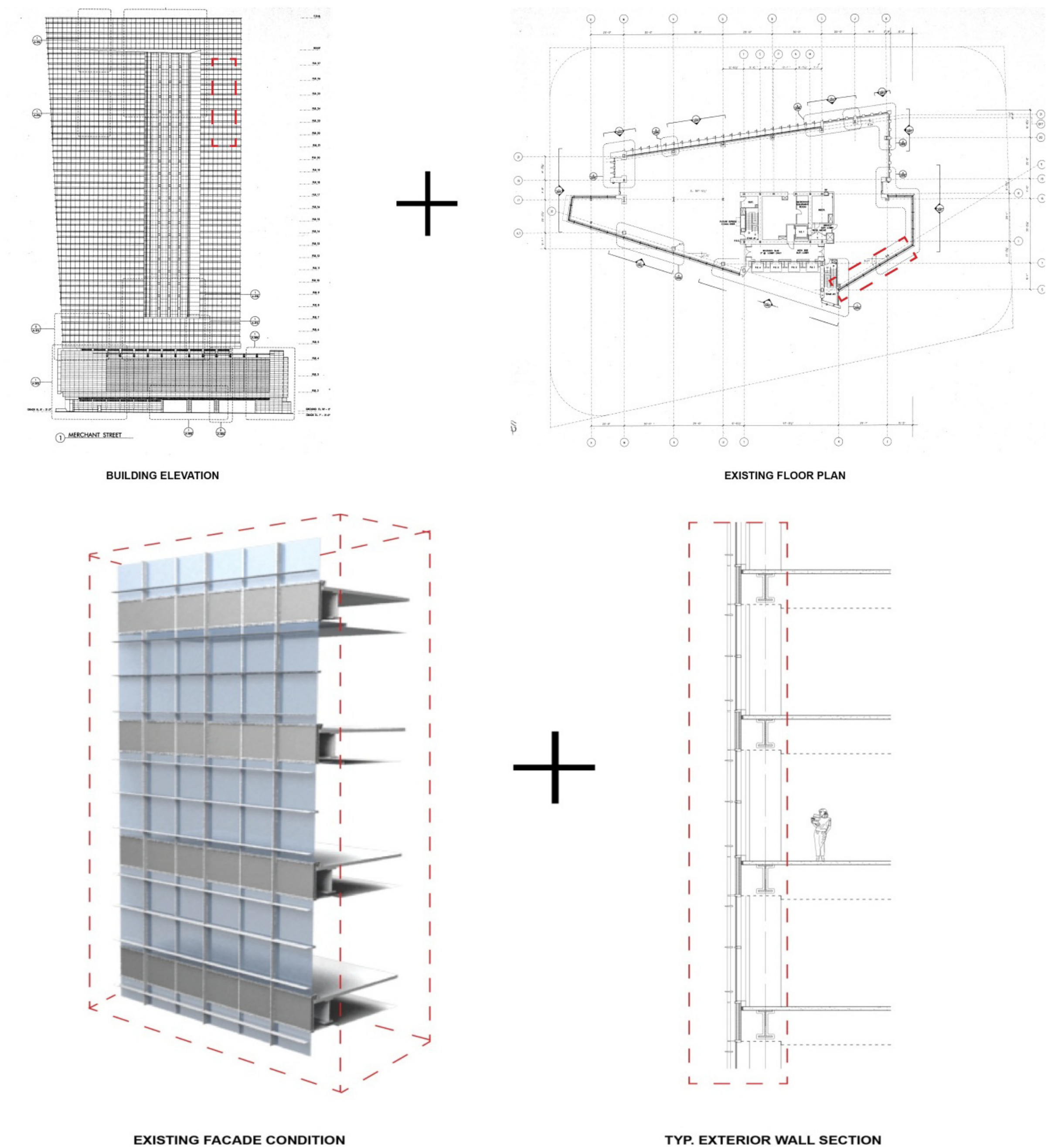


Fig. 2.1: Façade model under investigation will serve as the boundary conditions for all simulations.

By understanding the selected fenestration we can begin by identifying its major parts: exterior curtain wall with Low-E vision glass, verde maritaca granite spandrel condition and extruded aluminum horizontal louver sunshades. The typical curtain wall module is 5'-2" wide by one story tall, attached at each slab floor line. The current assembly is also comprised of extruded aluminum louvers with a 5' vertical spacing located 2" away from the curtain wall vision glass.

2.2. Thermal and Energy

Thermal design analysis of the existing façade requires various simulations which will help to make sense out of the mountains of data. However, the real key is being able to understand what exactly is going on in the building. This means being able to capture some patterns that defines the thermal state the façade design is currently in, which then allows one to compare it with various design scenarios. Thus, any changes in the current design can be focused on moving the current pattern towards the desired condition. By understanding the current conditions, a clear validation process can be established by which one can objectively judge subsequent design decisions.

Heat Gain

By estimating skin heat flow one can begin to understand its contribution to the building's cooling requirements. The amount of heat that is transferred through a buildings skin due to temperature differences between inside and outside is dependent on the size of the difference, the resistance to heat flow by the skin materials, and the area of the assembly. Heat flows from hot to cold and with a cooler interior temperature, heat will flow into the building. This rate of heat flow through the buildings skin is described in terms of resistance (R). Because glazing is more thermally conductive than insulated skin, much more heat flows through the glazing per unit area than the opaque surfaces.

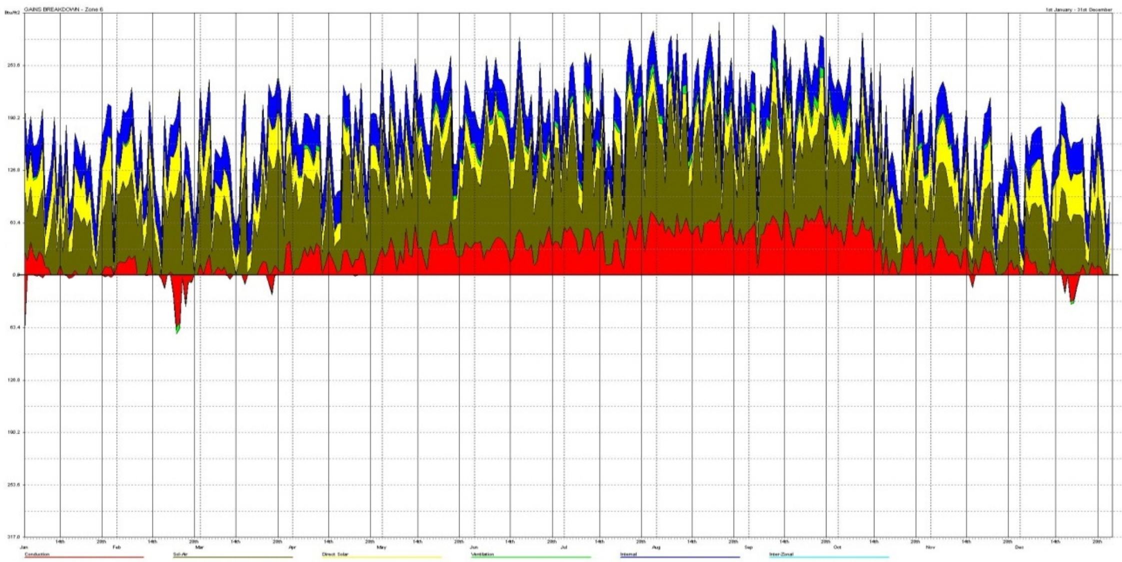


Fig. 2.2: Thermal calculation of yearly thermal gains breakdown.

This figure generates the yearly passive gains breakdown within the existing façade condition. The passive gains breakdown graph maps gains and losses that occur via the various heat transfer methods that occur within the space. These include conduction, sol-air, direct solar, ventilation, internal and inter-zonal gains and losses indicated by the colors shown in the legend below the graph. Values above the horizontal 0 axis indicate heat gain entering the space where as values below the axis indicates a heat loss. The graph is presented in two parts; the graph itself shows individual breakdowns which are measured in Btu/ft^2 for the specific boundary condition. By breaking down the graph we can present the gains as percentage values relative to the total amount of heat gain and losses. This is important to be aware of when comparing results between different gains breakdown graphs.

The passive heat gains breakdown graph shown above indicates that the majority of heat gains (44%) occur through Sol-Air heat transfer, indirect solar gains. This suggests that changing the color of the assembly to be lighter should reduce the indirect heat gains. The graph also shows that 18% of the total heat gains occur through solar radiation and 15% of the total heat gains through the buildings fabric via conductive heat transfer. With this understanding we can begin to see the importance of having external shading devices that protect from solar radiation as well as using materials that have a low U-value.

Hourly Temperature

These graphs display hourly temperature patterns within the space (without HVAC conditioning) on a temperature/time graph, time running in the x-axis and temperature in the y-axis. The selected boundary condition of the space is highlighted as a solid green line. In order to show the influence of climactic factors on the temperature pattern on the space, outside air temperature, solar radiation, and wind speed are also displayed as dashed lines. The solar radiation scale is shown on the vertical axis on the right-hand side. It is therefore possible to see why there is an increase in temperature during the day when the Suns radiation will affect internal temperature gain.

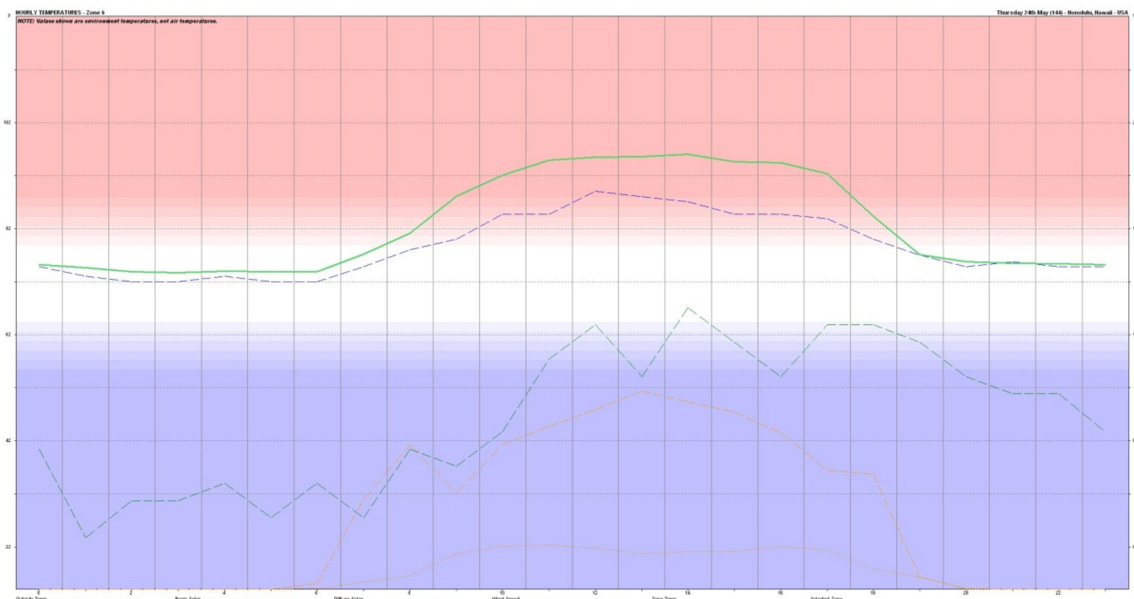


Fig. 2.3: Hourly temperature graph showing internal temperatures for the hottest peak day.

The primary information on this graph is the comparison of temperature fluctuations. Within the figure above the existing condition within the space provide an uncomfortable condition throughout the day. The internal temperature is unstable as it rises to a temperature of 94^{o}F at 12:00pm but falls quite rapidly to 75^{o}F after the sun goes down. The overall rate of change in the internal temperature suggests that moderating thermal effects of the space must be addressed. Looking at the solar radiation line, the noticeable rise between 9:00am and 12:00pm is directly associated with the corresponding pattern in internal temperature. This suggests that the relatively exposed south surface of the existing façade, the shading devices should be revised to provide more protection from radiation. It is also important to note that with the increase of internal temperature due to solar radiation, the building is forced to offset the temperature differences with the use of mechanical systems, increasing the cooling load of the overall system.

Hourly Gains and Losses

While internal temperatures are useful, it is necessary to be able to identify exactly why a temperature change occurred. Understanding the balance between heat gains and losses of each component will prove to be a valuable tool. An hourly gains graph begins to break down each individual component throughout the day and the specific energy flow. Conduction gains are shown in red and refer to flows through the external façade due to the differential in is temperatures between inside and outside. Solar gains in yellow refer to the direct radiation into the space through the vision glass of the fenestration. Internal gains in blue refer to the effects of lighting, equipment use and occupancy where ventilation in green refers to both infiltration and ventilation.

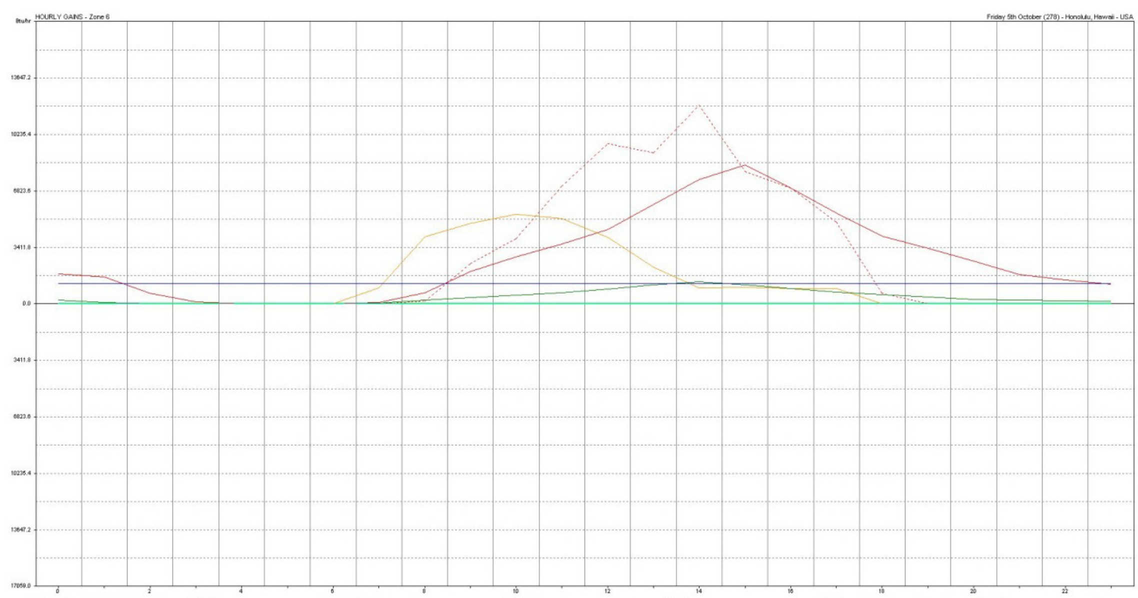


Fig. 2.4: Hourly heat gains and losses graphs for hottest peak day.

The graph shows the hourly gains for the hottest peak day, May 24th. As you can see the space is not conditioned which is represented with no HVAC load. It is clear that the major sources of heat gain in the space are by conduction, radiation and sol-air. All of which contribute an increase in internal temperature throughout the day. The source of solar gain peaks during the morning hours of the day due to the specific orientation of the envelope. Comparatively we can see that the corresponding temperature gain in the hourly temperature graph occurs in correspondence with the hourly heat gains. Finally, we can see that there is no heat loss within graph.

Temperature Distribution

In addition to hourly temperature graphs, which provide building performance over one day, the temperature data taken over the whole year shows the number of hours the space spent at different temperatures throughout the year. The vertical axis shows the hours for each temperature whereas the horizontal axis shows the temperature.

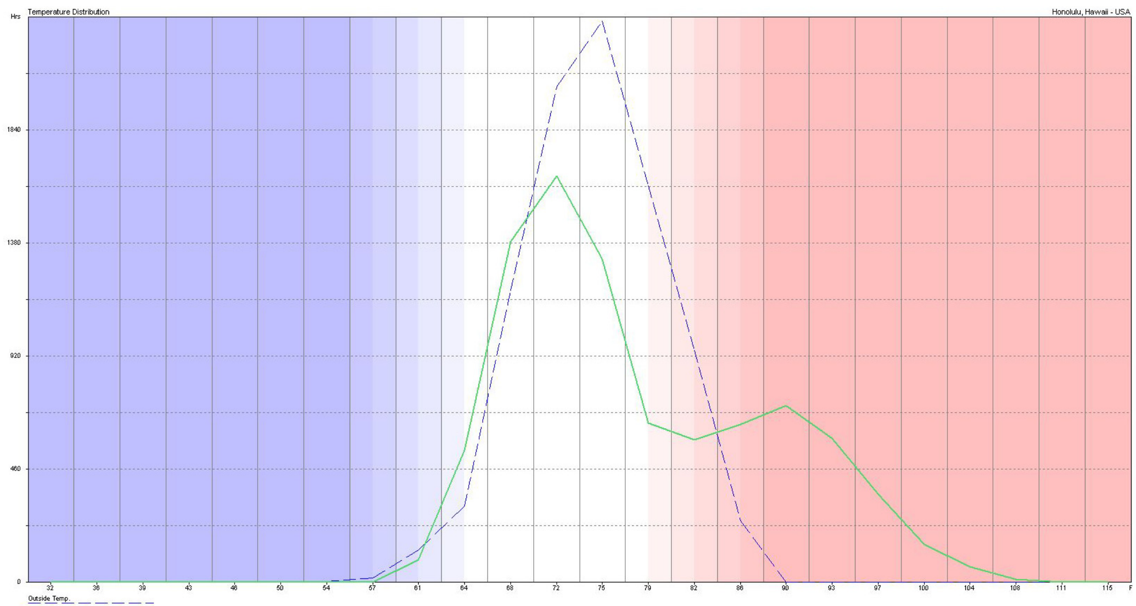


Fig. 2.5: Annual temperature distribution graph showing the number of hours each temperature occurred.

The graph shows the range and frequency of temperatures experienced both inside and outside of the building. The dotted blue line shows the external air temperature and the solid green line indicates internal temperatures. The shaded areas in the graph represent the comfort band. In the above graph, the inside air temperature of the model spent 5541 Hrs. (63%) in the comfort zone. The goal is to essentially have the space spend all of its time at the center at comfortable conditions. Any time spent in the blue or red zones indicate occupancy discomfort. Thus, any design decisions that compress the extents of the temperature range closer to the center will help to increase the amount of time spent within acceptable comfort conditions.

Monthly Average Hourly Fabric Gains

The following graph shows the hours of the day in the vertical y-axis and months of the year in the horizontal x-axis. Each grid-square represents the gain for that hour averaged over the specific month. The result is an annual pattern of both diurnal and seasonal variation. The graph shows the values of conduction gain through the building fabric for the existing fenestration assembly. Given the specific context, the hottest temperatures occur in the summer months from May to September. We can see in the graph that the maximum conduction gains are occurring from around 12:00pm to 4:00pm on a September afternoon. Given that this occurs during one of the hottest months of the year, this can cause considerable problems for occupants. With this condition, an increase in the cooling requirements is needed in order to offset temperature differentials.

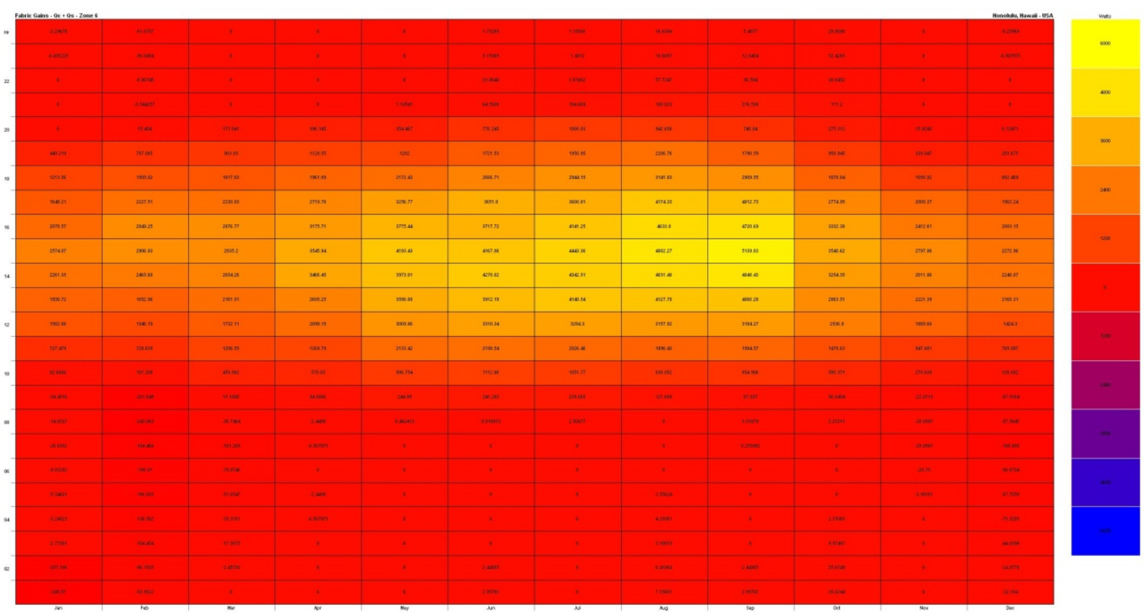


Fig. 2.6: Monthly average hourly conduction gains through the fabric showing diurnal patterns of the given context.

Monthly Average Hourly Solar Gains

Displaying façade gains is useful as it is one of the only ways to fully understand the effect of thermal mass on the building response. The following graphs isolate the two components of solar radiation, direct gains through transparent elements and indirect gains due to sol-air temperature effects.

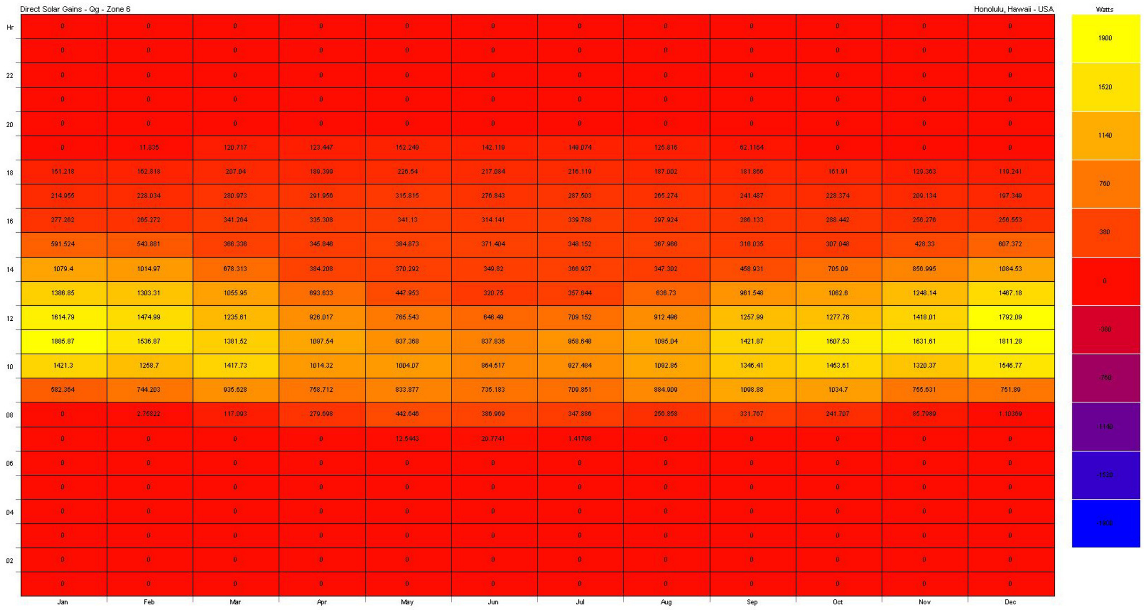


Fig. 2.7: Monthly average hourly direct solar gains.

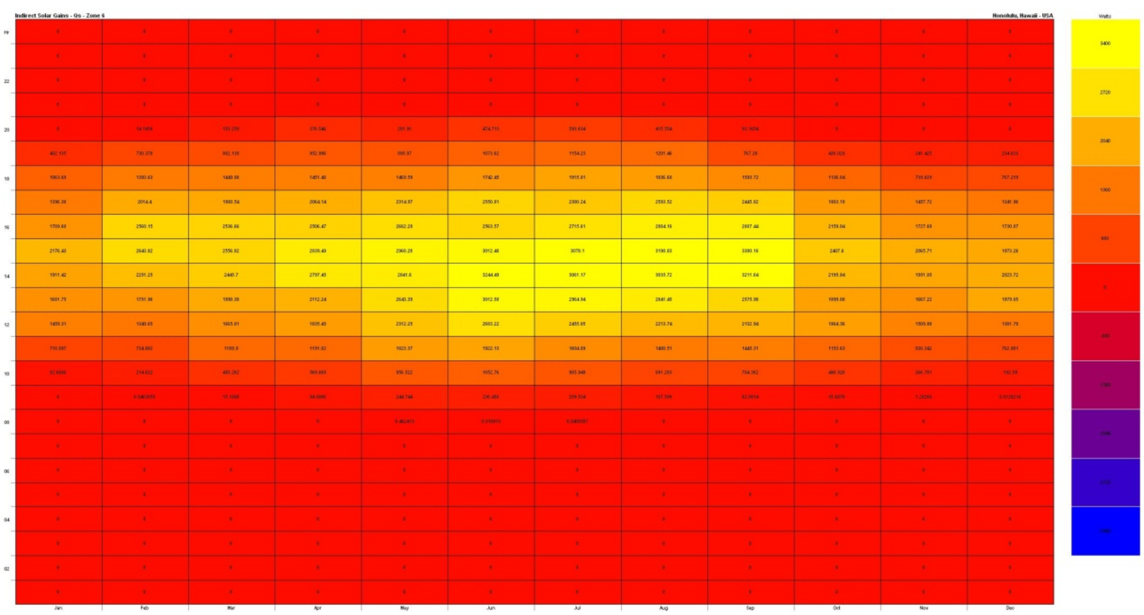


Fig. 2.8: Monthly average hourly indirect solar gains.

A comparison of the direct and indirect solar gain patterns clearly show that the lag effects of the external façade. It is quite clear that the exposed south façade is the source of delayed fabric gains from around 1:00pm on summer afternoons.

2.3. Solar Exposure

In the design and analysis of the existing façade, solar exposure will play an important role in providing a high-performance solution. The level of exposure from the sky into the internal spaces is a key factor in the design of energy efficient facades. Properly understood, it can result in substantial benefit in controlling solar heat gains, shading devices and daylighting strategies.

Incident Solar Radiation

The amount of solar radiation transmitted through the skin of the building is relative to the size of surface area, orientation, and heat transmission characteristics of the exposed surfaces. Since the solar heat gain through glazing can be fairly large, understanding the amount of incident radiation that will strike the façade will help to determine specific measures or methods of reducing the solar load. With a wide spectrum of radiant energy from the sun which strikes the surface of the façade it is important to mitigate the total amount of radiation that is absorbed, transmitted and reradiated to the interior. Using cumulative insolation analysis, it is possible to display the distribution of solar radiation over the selected face of the façade. This study can be particularly useful when considering existing shading as well as identify specific design requirements or assessing the potential of placing building integrated photovoltaic (BIPV) for maximum collection.

The following diagram illustrates the amount of incident solar radiation that strikes the façade throughout the year. A brief evaluation of the assembly shows that the existing horizontal louvers provide moderate protection as seen with dark purple. These external shading devices of the assembly help control the solar gains. Its general idea is to intercept direct beam radiation before it enters the building. Once direct sun enters the building, the only way to get it back out is through reflection or indirectly through convection.

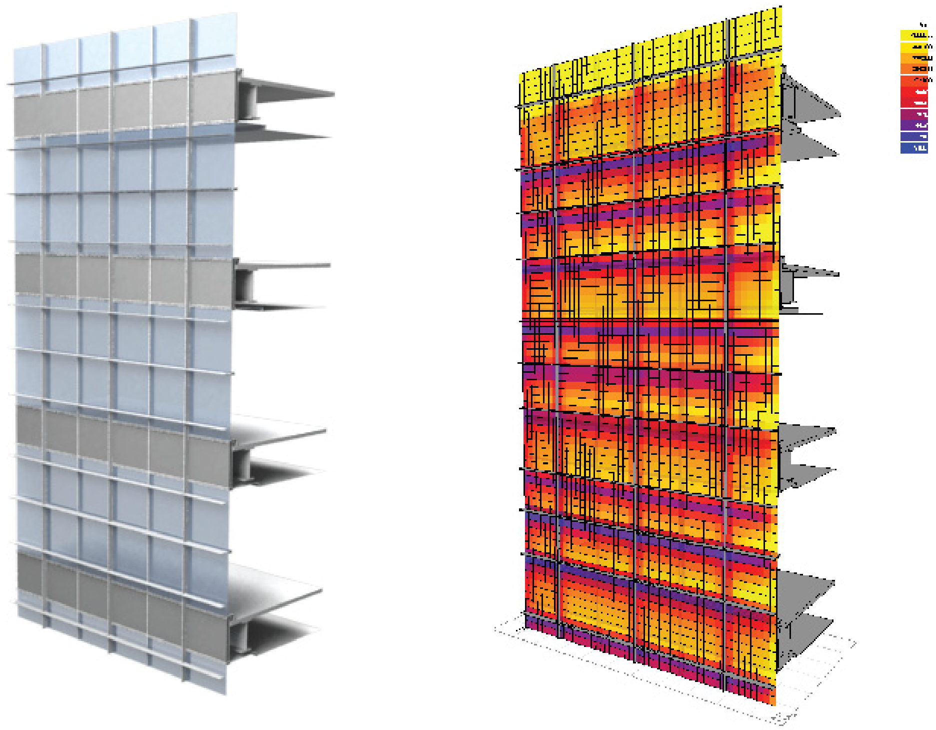


Fig. 2.9: Incident solar radiation analysis on the existing façade assembly.

The current method for exterior solar control has been designed to shade the surface of the building but falls short at fully protecting the entirety of the façade. While this fixed system is designed mainly for solar shading, an operable system can be used to control thermal gain, reduce glare, and redirect sunlight. For the existing climate, the system is more efficient being placed on the exterior of the building, blocking the solar radiation before it strikes the envelope.

The following graph illustrates the percentage of unobstructed solar radiation that strikes the face of the existing model. It shows the hours of the day in the vertical y-axis and months of the year in the horizontal x-axis. Each grid-square represents the average percentage for that hour over the specific month. The result is an annual pattern the total incident solar radiation exposure.

TOTAL MONTHLY DIRECT SOLAR EXPOSURE

	AVAIL.	AVG	REFLECT	INCIDENT		ABSORBED		TRANSMITTED	
MONTH	Wh/m2	SHADE	Wh/m2	Wh/m2	TOT.Wh	Wh/m2	TOT.Wh	Wh/m2	TOT.Wh
-------	--------	------	--------	-------	--------	------	--------	-------	--------
Jan	138450	52%	0	39311	1242875	10249	324034	18014	569548
Feb	135147	57%	0	29879	944661	7707	243664	13692	432891
Mar	145459	63%	0	25561	808142	6548	207035	11713	370331
Apr	140102	73%	0	13494	426633	3325	105134	6184	195505
May	166382	83%	0	9589	303165	2328	73615	4394	138925
Jun	182608	86%	0	7080	223848	1644	51991	3244	102578
Jul	184705	86%	0	8664	273919	2069	65423	3970	125523
Aug	175462	79%	0	12631	399349	3108	98262	5788	183002
Sep	167854	67%	0	24613	778189	6180	195376	11279	356605
Oct	141676	58%	0	30112	952021	7790	246303	13799	436264
Nov	116241	51%	0	30493	964084	7922	250464	13973	441792
Dec	125119	46%	0	40099	1267798	10458	330642	18375	580968
-------	--------	------	--------	-------	--------	------	--------	-------	--------
TOTALS	1819205		0	271526	8584685	69329	2191944	124427	3933932

The graph proves that during the winter months where the sun angle is fairly low, the existing model has a high exposure percentage. During the winter solstice, the maximum level of exposure can reach as high as 80%. This demonstrates the need for the existing façade application to reduce the level of solar exposure when low sun angles are present. A detailed analysis on the total monthly solar exposure of the simulated model will help to understand the amount reflected, absorbed and transmitted of the existing fenestration system.

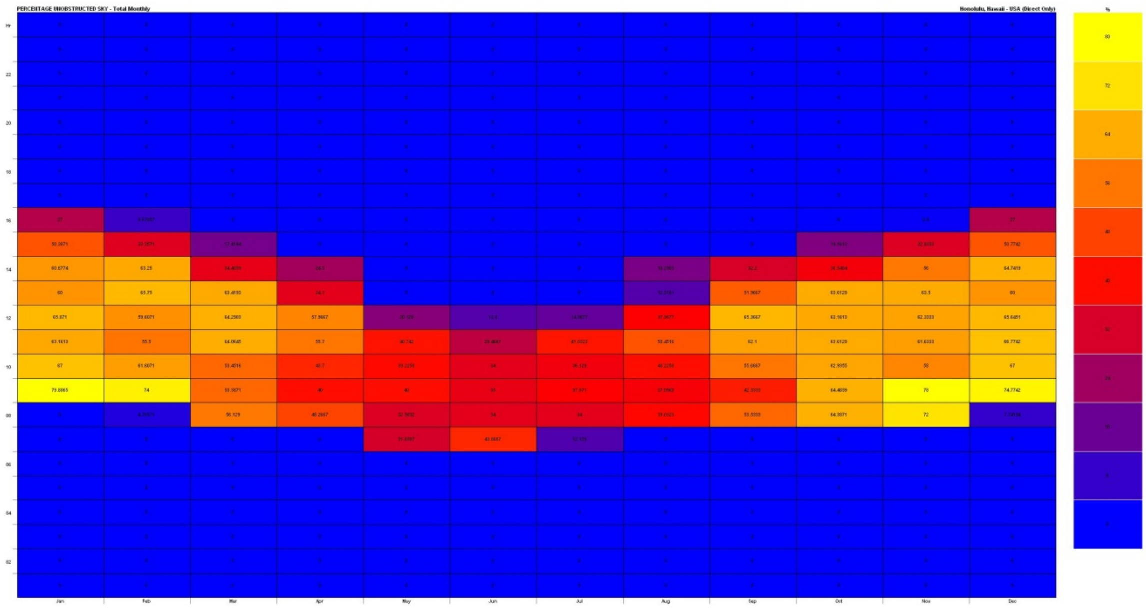


Fig. 2.10: Percentage of unobstructed solar radiation striking the surface of the façade.

At the same time we can begin to analyze the percentage of the existing shading and its ability to mitigate excessive solar heat gain by means of blocking the existing solar radiation. The external shading layer on the outside of the façade shades the glazing and reduces solar heat gain. Horizontal shades provide effective shading on the south façade when the sun altitude is high. However, the current assembly provides very little protection during the morning hours when the sun angle is lower. Because the shading devices are in the direct sun, special care must be taken so that they do not transfer the heat they absorbed into the interior of the building.

Solar Rays

The current assembly is comprised of extruded aluminum louvers with a 5’ vertical spacing located 2” away from the curtain wall vision glass. The typical horizontal exterior projections implement a high reflectance surface to reflect incident sunlight to the interior depth of the building. Solar ray simulation used to identify the path of the sun’s rays that directly enter the building throughout the year helps to determine specific existing conditions that affect the buildings thermal and daylighting performance. The position of the sun varies according to the season and time of day and will have a significant impact on design decisions.

Since we have identified that the low sun angle during the winter months will cause considerable problems of solar heat gain as well as the lack of protection, it is critical to understand how path of the rays will enter the space. By understanding the angle and direction of solar rays, we can begin to identify possible design solutions what it comes to protecting the interior space.

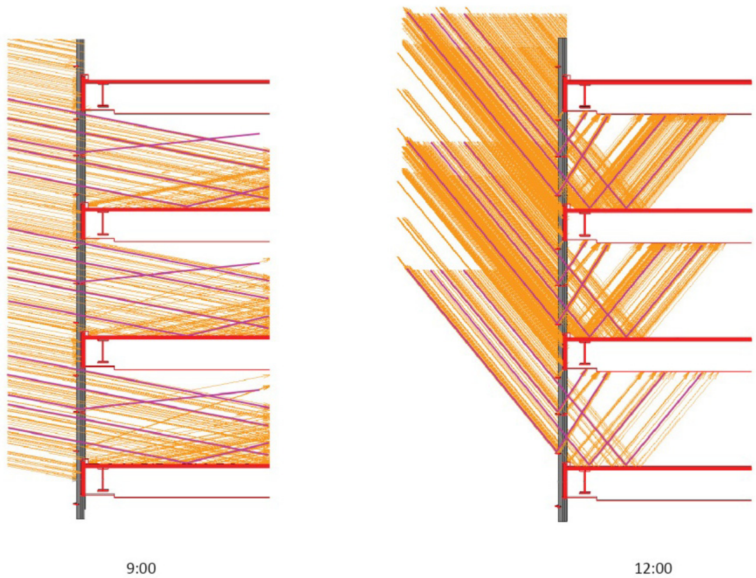


Fig. 2.11: Solar ray study during the winter solstice, December 21.

Conventional side-lighting techniques cause glare, high contrast and excessive brightness causing discomfort issues for occupants. Light-reflecting assemblies rely on reflecting and refracting to enhance the distribution of incoming daylight which enters the space. The benefit of improving distribution is not only the potential to offset artificial lighting requirements but to also improve indoor quality and visual comfort.

The understanding of how the solar rays enter the space during specific times throughout the year will have a critical impact of selecting the right shading device for the existing fenestration. It is important to note that while we would like to provide the maximum shading to protect the building from excessive solar heat gain, it is also important to not interfere on the visual aspects of the occupants inside. These factors include the use of daylighting as well as uninterrupted visual continuity to the exterior. Thus, when selecting the specific system, the resulting design should establish specific goals, limitations and constraints relating to the use of daylighting.

2.4. Ventilation

Based on the initial building study, we were able to see that the windward side of the building was subject to high wind velocities. However, on the south side of the building (the area of this study) was subject to updrafts due to the negative pressure effects. As we begin to understand the micro-climactic issues that surround the façade model, one can begin to see potential benefit of having such an updraft. Air flow simulations of the façade will help to make specific design decision when it comes to the geometry of the façade (height and width of openings, origin and destination of air, ventilation strategies, etc.). Using these specific wind flow patterns as an asset rather than a problem, the use of natural ventilation can provide a comfortable interior environment while reduce the buildings requirement for mechanical ventilation.

With the implementation of a naturally ventilated façade system, external air is brought into the system while warm air is exhausted. Two specific methods for this is wind pressure and/or stack effect. If properly designed to suit the existing environmental conditions, wind flowing over the façade can create pressure differences between the inlet and outlet, there by inducing air movement. Without wind the façade can still be ventilated through stack effect. As air flows into the inlet it is heated and becomes less dense and thermally buoyant. As a result, air will flow into the inlet and out the outlet removing heat. Because there is a potential for stack-driven and wind-driven pressures, the air path of the exterior need to be correctly understood in order to configure the exterior openings to insure proper ventilation.

However, natural ventilation does not come without risk as it may cause problems due to pressure, drafts, and unwanted humidity to enter the space. As a result, the air flow path must be properly designed so that solar heat gain can be removed efficiently and reduce interior temperature.

3. FAÇADE INVESTIGATION

Increasing interest in double-skin facades as an active responsive system continues to be explored in the European Union. Within the past decade there had been various buildings constructed with complex, interactive building facades which focus on fundamental strategies to increase thermal performance. It is important to note that while the double-skin façade strategy has been successful, applicability to the Hawai`i climate has not been explored. The European climate is significantly cooler that Hawai`i and the design of these facades have dominated northern climates. Hawai`i's location and the application of this system will require a different set of design solutions to meet performance requirements. In order to identify those strategies which may be applicable to warm and humid climates, a series of façade investigations must be explored.

Buildings with double-skin facades are a complex form of building systems which deal with issues such as thermal and visual comfort, cooling load, heat loss, ventilation, acoustics, moisture and fire safety. Various advantages and disadvantages of this building envelope are known and have been discussed in earlier chapters. Although the suitability of this façade construction is gaining popularity in northern climates, it may have potential benefits in Hawai`i. Existing commercial building with highly glazed facades tend to overheat when peak outside air temperatures linked with high solar gains, thermal discomfort for occupants increase along with cooling loads. To optimize thermal comfort and minimize cooling loads, the thermal behavior of the façade requires careful investigation.

The double-skin facades built in recent years vary in geometry and construction due to specific design requirements. Poirazis presents a collection of buildings with double facades and the literature available on the subject. [71] By classifying the diversity of the double-skin façade according to geometry and ventilation concept, one can begin to identify thermal behavior and the number of parameters involved. The following section focuses on the thermal simulation of the presented buffer façade approach in an attempt to find a suitable design option which illustrates a method of application focusing on; insulation, energy balance, and ventilation of double-skin façades upon the existing model.

[71] H. Poirazis, Double-Skin Facades for Office Buildings, Lund University, Sweden, 2004.

3.1. Design Requirements

The primary objective of any building envelope is to provide thermal, visual, and acoustical comfort with minimum energy consumption. Therefore, controlling physical environmental factors must be considered during the design process. When it comes to the design of double-skin facades, there are not a set of guidelines, but rather sources listing best practices. However, criteria that apply to single skin facades can also be applied to double-skin façade. The following section outlines parameters for thermal performance with respect to the local environmental conditions. Variables that affect the performance of the faced are:

External Environment

- Air temperature
- Solar radiation
- Humidity
- Wind velocity

Site

- Dimension and location of surrounding buildings
- Solar radiation reflected from surrounding surfaces

Building

- Orientation
- Building function
- Form
- Type of ventilation
- Thermal and energy loads

Space

- Position within the building
- Dimension and geometry
- Orientation

Building Envelope

- Material properties (type, thickness, conduction, absorbance, reflection, etc.)
- Air cavity dimensions
- Façade type (single, multiple)
- Ventilation mode (natural, mechanical, mixed mode)
- Shading

System components, geometry, and ventilation of the double-skin façade depend on the location and existing characteristics of temperature and airflow within the intermediate space. For example, the air temperature, radiation and wind velocity on the selected investigation will greatly impact the design requirements. When selecting the construction of the system, decisions must be made for material properties, glazing type, air cavity and ventilation and size and location of air intake and outlet (outside to outside, inside to inside, outside to inside, etc.) and providing for shading. Oral in his research on building for envelope design, presents a selection process for the double-skin façade that address these comfort parameters.[72] The basic process is that environmental conditions, building and facade properties are utilized as constraints and opportunities in selecting building envelope alternatives.

Building performance requirements for double-skin facades consist of physical behavior, energy performance, thermal comfort, visual comfort, fire protection, etc. As mentioned in previous sections, specific characteristics of the site affect the buildings thermal performance, therefore development of strategies that are context-based are considered and has helped in evaluating specific control strategies. Because energy consumption is closely related to thermal performance, selecting design strategies applicable for this specific climate must be tested.

Since the geometry and type of double-skin facades are critical for the function of the overall system, a brief classification of façade types and their function will serve as a starting point. The function of the façade and the thermal performance strategy of the system are closely dependent on the temperature and air flow of the air between the layers. The main characteristics that influence the properties of the façade assembly are:

- *Ventilation:* Both the origin of the air flow and the destination of the air flow; whether it's inside, outside, both or none at all.
- *Solar control:* Identifying the heat transfer of the system, the position of the shading devices, and their potential to mitigate solar gains; specifically minimizing solar heat gain entering the interior within hot climates.

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[72] Oral, G.K., Yener, A. K., Bayazit, N. T., "Building Envelope Design with the Odjective to Ensure Thermal, Visual and Acoustic Conditions", Building and Environment, Vol. 39, pg. 281-287 (2004).

- *Construction:* Identifying the structure of the assembly, the specific width of the cavity space and its subdivision; all which depend on the existing wall assembly.

It is obvious that different classifications can lead to different system solutions. Thus, it is extremely important to be focused on the main goals and constraints of the existing condition. By establishing these constraints, one can begin to identify characteristics that will influence the desired performance, making for a more successful design solution.

Research in the changes of these characteristics within the double-skin facade has provided useful information as to how the air temperature and ventilation changes for different configurations. These scenarios, when design constraints are considered, can be edited to what is feasible within the existing building and provide a better understanding of the system configuration that might be most favorable with the environmental context.

Based on the information collected through research and case study data, investigation into their proposed solutions on their individual problems and requirements helps to break down specific design strategies. Efficient application of a double-skin façade retrofit is mainly related to the application of systems and techniques dealing with the enhancement of thermal performance within the existing building. Actions aiming at improving the envelope of the existing building have been found and focus on the following categories:

- Reduction of heat transmission through the buildings envelope.
- Improvement of natural ventilation and solar control.
- Create a building envelope that will allow the passage of external air to flow through the building.
- Use fenestration elements adjacent to the facade openings to enhance airflow.
- Use envelope assemblies with low thermal capacities to minimize heat storage.
- Employ light-colored finishes for exterior surfaces of the vertical envelope.
- Allow the use of operable window assemblies.

Retrofitting actions aiming to improve thermal comfort conditions and decrease the cooling load of the building involves the following strategies:

- Strategies aiming to decrease solar and internal heat gain in the building. These include the use of more efficient and appropriate solar control devices, as well as minimizing thermal transmission.
- Strategies aiming to modulate the solar and internal gains in the building. These involve the use of night ventilation as well as techniques that take advantage of thermal mass.
- Strategies aiming at dissipating the excess heat of the building into a heat sink like the ambient air. These involve the use of natural ventilation strategies within the fenestration.

Specific constraints relative to the existing context and fenestration assembly has been established within the following categories:

- *Façade Assembly:* Provide an interactive wall system which allows for operability of both the inner and outer skin layers. This system proves ideal for hot climates with high cooling loads as the advantages of this system in terms of thermal performance allows the use of natural ventilation within high-rise buildings.
- *Construction:* Due to the existing structure of the building and the wall system, the structure of the double-skin needs be cantilevered from the slab edge. This is due to the lack of load bearing capacity of the existing curtain wall itself. As a result, the width of the air cavity between the two layers shall also be minimized. Partitioning of the assembly shall also be considered as it relates to the construction of the system.
- *Ventilation:* The origin and destination of air flow within the system must be interactive and allow for an effective method of heat load removal with the use of purge ventilation. Due to increased temperature and the high level of solar gains, natural ventilation must be utilized to control the temperature of the cavity space as well as the internal environment.
- *Solar Control:* Since the amount of solar heat gains through the façade plays a large role on the thermal performance of the building, heat transfer must be minimized with the implementation of external shading devices which provide maximum protection. Visual integrity of the system must also be considered.

As described above, if the design of the façade is able to realize the function and flexibility of the system, while considering the existing constraints, the selected system being considered can be optimized to increase the function of the façade (i.e. providing natural ventilation, better control of heat gain of the façade, etc.) and determine details with respect to the mentioned design parameters in order to fulfill the stated goals.

Various authors have investigated the thermal behavior of double-skin facades. Also specific components such as the importance of understanding the correct inlet and outlet temperature and the composition of the cavity space have been studied. Nonetheless, the thermal behavior of building with this type of envelope remains a challenging task within Hawai`i's climate. As yet, no single façade configuration that uses the strategies of the double-skin façade has been tested within this specific climate.

The selected scenarios will be designed and scrutinized by its thermal performance and compared against the performance of the existing fenestration of the building. Only then will the use of double-skin façade systems be considered for its potential to become an interactive building element which focuses on fundamental strategies to increase occupancy comfort specific to Hawai`i's climate.

3.2. Approach

Simulation of the model helps to represent real physical occurrences and simplify reality into the modeled façade condition. As a result, the study has to be streamlined in an appropriate way in order to obtain a simulation model. As mentioned earlier, the large building with similar rooms and fenestration assemblies can be reduced into a small number of representative floors to represent the boundary condition. An examination regarding the possible implementation of double-skin facades within warm and humid climates requires analysis of internal and external heat gains of the selected design configuration, identifying those that are potentially critical. These helped to select the appropriate boundary conditions defined as well as helped to identify what will need to be model. This investigation will focus on two major elements that affect the thermal performance of the double-skin façade; energy flow paths and air flow paths. Standalone modeling and simulation tools exist on both levels.

However, the limitations of the model can only be overcome by coupling the energy model with a CFD tool. As a result the challenge is to couple the models to provide more accurate results.

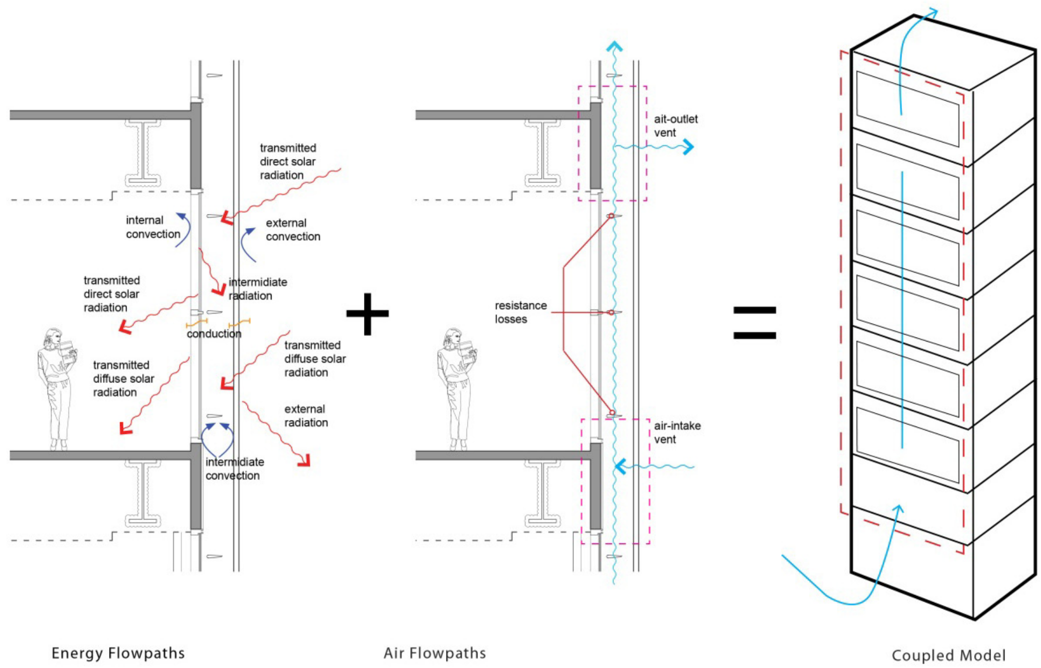


Fig. 3.1: Schematic representation of the super-imposed thermal and airflow network models.

Energy Flow Path

A double-skin façade is comprised of several layers; for example a typical system is comprised of an insulating glazing unit, a shading device, and an external single pane, totaling in four layers with an intermediate air cavity. In a case where all layers are parallel to each other, the use of DesignBuilder will be applied in determining the temperature and heat gains in each specific node. At the interface of two different layers, reflections occur and these multiple reflections at different layers have to be taken into account. To illustrate this, the selective transmission of solar radiation through each layer of the façade will be identified. Where shading devices are used, the geometry of that assembly and reflections on the surfaces similarly will require consideration. The incident angle of solar radiation (dictated by the façade orientation, location, date and time) plays a large role in calculating absorbance in the layers of the façade. For a given solar irradiance, the absorbance calculated can be used to determine heat sources of each layer. As a result the energy balance of the system must be modeled and simulated within each node of the multiple layer skin system.

The primary idea is to determine the temperatures of all surfaces in the façade model and solve the overall heat balance. The heat balance for the different layers of the façade includes conduction, convection and radiation. When the air flows are calculated, the output is used to calculate the convective heat transfer coefficients of each individual surface.

Air Flow Path

The thermal behavior of double-skin facades (the microclimate in the façade) is significantly affected by the airflow within the system. In addition to heat sources on surfaces, the geometry of the building and specifically the façade, ambient temperature, wind etc. determine the flow pattern, flow rates, and ultimately the temperature distribution and heat flows. Research and experimental investigations by Manz have shown that airflow patterns in the façade cavity can be quite complex (i.e. recirculation, vortexes, counter flows, etc.) frequently occurring and that actual airflow patterns may differ from the intended behavior.[73] Thus, simulating the complex airflow patterns and convective heat transfer of surfaces play a major role and require modeling. As the computational fluid dynamics (CFD) technique incorporates all these features, it will be the model of choice where predictions are needed. The required computing time remains a major drawback of the CFD technique and sets a limit to its practical application within this project. Therefore, simulation of complex geometries, such as those occurring in the façade application will be restricted to a steady-state case with simulations over short periods of time. As a result, the air flow path simulation will investigate the temporary thermal behavior of the façade during peak solar exposure. The airflow simulations of the cavity will focus on identifying:

- Mass flow and direction (amount of air that enters and leaves the cavity)
- Simulation of vertical temperature distribution in the cavity

If the airflow in the system is mechanically driven, then the amount of air flow in the cavity is known. However, since the use of naturally driven air flow is used, it is necessary that the flow be calculated. In addition, the airflow in the cavity should be controlled to maintain the required airflow rate in the interior spaces. Air temperature in the façade cavity is essential to

[73] H. Manz, A. Schaelin, H. Simmler, Airflow patterns and thermal behavior of mechanically ventilated glass double fac¸ades, Building and Environment 39 (2004)

maintain a comfortable indoor environment, especially when the air is used for ventilation of the interior space. Because air temperature and the airflow in the cavity are interrelated parameters, one cannot be simulated without the other.

3.3. Simulations

During the planning and design process, recommendations for the design of double-skin layers are to select appropriate control strategies relating to glazing properties, establishment of shading devices, and height of the cavity. Since these parameters are greatly dependent on the environmental context of the existing building, predicting energy performance early in the design stage can influence design decisions. Traditional techniques for controlling the internal microclimates within this type of environment include the use of low-e glazing to reduce heat transfer, appropriate location and orientation of buildings to introduce natural ventilation within the building, and the use of HVAC to provide needed cooling. In analyzing appropriate design strategies that are dependent on the existing building and environmental conditions, comparison between single and double-skin facades is a practical option.

Using the results of the previous energy analysis one can begin to test designs in order to identify the appropriate facade solution; one which reaches project goals, maximizes building performance, and minimizes energy usage. Energy modeling will be used to determine the most effective solution along with many other considerations. (Define project goals and solution, energy modeling to determine appropriate solution.)

Research on design strategies and performance of the double-skin specific to this climate are extremely limited. However, one of the few studies specifically focus on the comparison between single and double-skin facades in hot climates and have found that single skin facades account up to 45% of the buildings cooling load and that with careful material selection, double-skin facades will result in substantial decrease in peak and annual cooling loads.[74] In this study, Hamza analyses a multi-story external air curtain double-skin with a 1 meter cavity. Using a higher SHGC and reflectance value than transparent glass on the external

[74] Hamza, N., (2008). "Double versus Single Skin Facades in Hot Arid Areas", Building and Environment, Vol. 40, pp. 240-248.

layer of the double-skin façade offers a first line of defense against the assault of the direct solar radiation in Hawai`i's climate. In this case, the visual continuity between the inside and outside in maintained without interruption from other solid and heavy shading materials that are currently used in building within this region. Results indicated that clear glazing for the external layer of the façade increases energy consumption compared to a single skin. However, tinted and reflective glazing significantly lowered energy consumption. This study did not analyze the effects of changing the dimensional height of the air cavity.

In order to study the effects of changing design parameters, such as the effects of opening locations and cavity dimensions, different design scenarios were investigated for a double-skin wall. By preserving the existing façade and using it as the inner skin of the system the addition of the second skin focuses on enhancing the existing façade by increasing heat insulation. Static variables for all double-skin scenarios were location, weather data, occupancy and equipment loads, air change rate, etc. as seen in the following table.

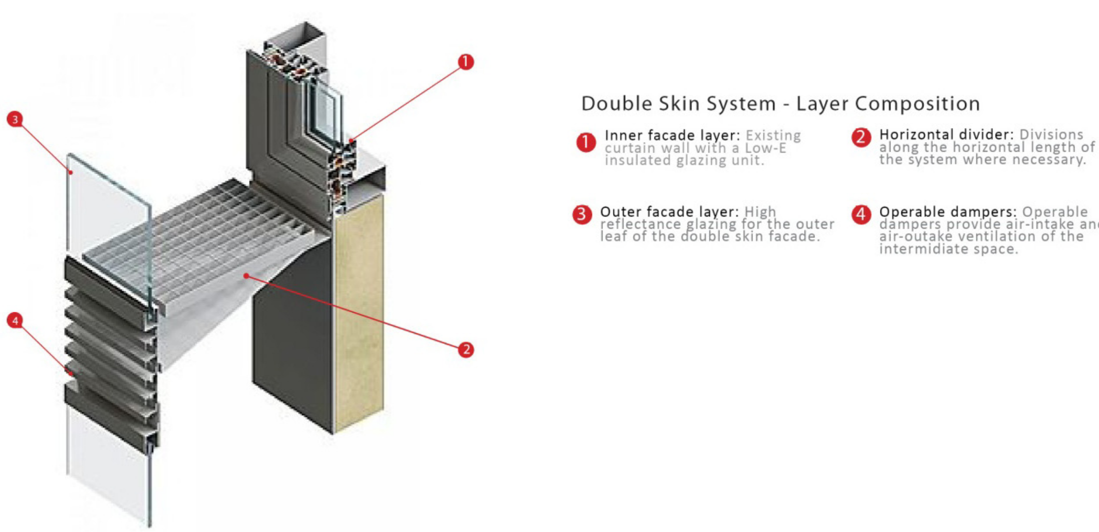


Fig. 3.2: Proposed double-skin system layer composition.

All Facade Types

Location	Honolulu, HI
Orientation	SE
Activity Template	Generic Office Area
Cooling setpoint temperatures	
Cooling	75.2
Cooling set back	82.4
Occupancy	7 am to 7 pm
Occupancy load	0.1 people/ft2
Lighting requirements	37.16 fc
Equipment load	1.09 w/ft2
Air change per occupant	21.189 ft3/min-person

Double Skin Facade

Type	Multi-story, single & hybrid
Air cavity	24 inch
Ventilation mode	Natural
Air flow type	Sealed inner skin (exterior vent supply, exterior vent exhaust)
Glazing type	
Inner	Low-e (double glazing)
Outer	High-reflectance (single glazing)

As for the outer skin, several scenarios were investigated with changing design variables, such as air cavity height as well as location of openings. Case studies found within this research have helped to establish three different design scenarios using their methods of environmental control of the façade as it relates to thermal regulation. The intention of this study is to recognize how existing models which have specific characteristics unique to their assembly can be altered for this specific context based design approach. Each case study has been slightly altered as needed in relation to design requirements.

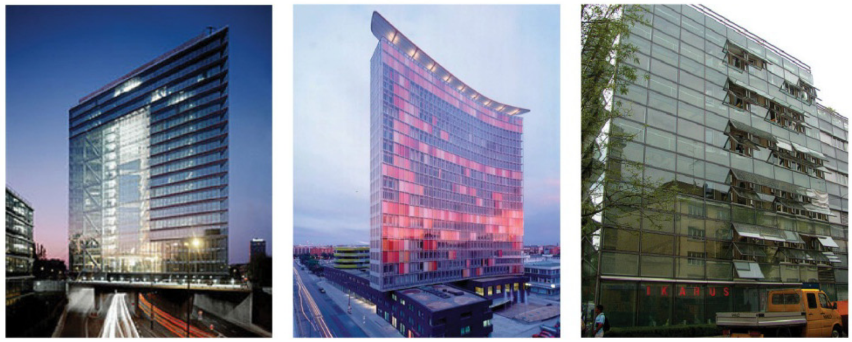
The following diagram clarifies the developed scenarios that were derived from each specific case study. The design variables such as cavity height and ventilation control systems will be further explored through the analysis approach mentioned in the previous section. Each specific scenario will be simulated individually, focusing on energy flow and air flow as well as specific design strategies related within the façade assembly.

CASE STUDIES

Stadttor

GWS Headquarters

SUVA Insurance Co.

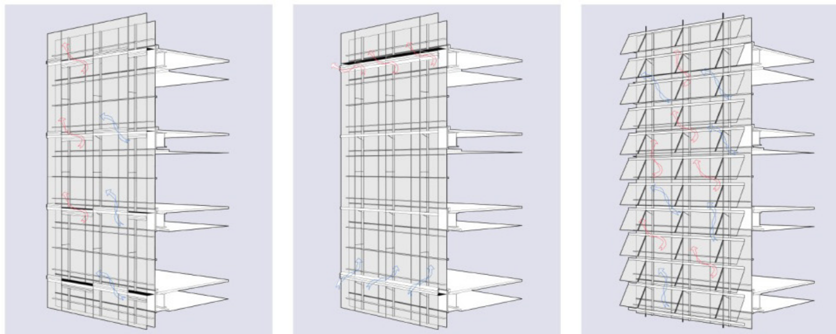


DESIGN STUDIES

Single Story Corridor

Multi-story Shaft

Dynamic



DESIGN VARIABLES:	**SCENARIO 1:**	**SCENARIO 2:**	**SCENARIO 3:**
SYSTEM TYPE	**SINGLE STORY CORRIDOR**	**MULTI-STORY SHAFT**	**DYNAMIC**
	Sealed inner skin	**Sealed inner skin**	**Sealed inner skin**
Control System	Dampers (staggered)	Dampers (top & bottom)	Operable panels
Ventilation System	Diagonal airflow	Vertical airflow	Various airflow

Fig. 3.3: Design scenarios by façade type.

3.3.1. Scenario 1 – Single Story

This single height corridor façade scenario also consists of an external air curtain strategy as seen with the multi-story condition, creating an invisible layer which separates climate controlled interior air from outside temperatures. However, the construction of the system is split at the intermediate space between the two skins, sealing each floor at the slab edge. The single story façade has no vertical divisions except those that may be required for structural, acoustical, or fire protection reason. Here, air flow is expected to take a diagonal stream line across the intermediate space of the facade as air-inlet and air-outlets are staggered to prevent air exchange between openings. The occupied space behind the double-skin façade is again mechanically conditioned as the inner skin is sealed preventing natural ventilation of the interior building space. The destination and origin of air flow within this system is to and from the exterior environment. Natural driving ventilation and thermal buoyancy are the primary forces acting on the space and help to reduce the air temperature within the cavity as the warm air is expelled to the outside.

One of the advantages of the single story, corridor façade over other typologies is that corridor facades are not limited to the full height of the building. However, they do not utilize the stack effect as much as the multi-story assembly because the linking effect will be broken at each floor. The ventilated double-skin limits the required cooling loads by ventilating away the solar heat buildup within the cavity. A central aspect of this system in addition of the second skin is to minimize temperature distribution within the single story cavity by reducing its height and constantly ventilation the intermediate space. As a whole, the system looks to provide maximum solar protection while reducing air temperatures within the façade assembly.

The brief was to provide a single story façade assembly which would decrease cavity air temperatures while still providing solar protection. Focus has been placed on the single story construction system that is one of the oldest construction types for double-skin facades. The following section will describe the specific construction techniques and energy strategies used within this system as well as provide simulations aiming at identifying both the energy flow and air flow within this type of system. Lastly, observation of the specific qualities of the system will be discussed in terms of its viability within the existing context.

DESIGN STRATGIES

Ventilation boxes at each floor level have been integrated into the depth of the intermediate space with automatically controlled dampers. The air-intake and extract openings in the external skin are located near the floor and ceiling and are staggered from bay to bay to prevent unwanted hot air extracted on one floor entering the space on the floor immediately above. These vents can be completely operable and become fully opened to allow for the maximum amount of air to flow into the system. The regulation of cavity temperature levels is regulated through the use of increasing ventilation ejecting the hot air away from the building. Maximizing the glazing of the system ensures that maximum exposure to daylight and views will not be reduced. However, the horizontal blinds located behind the outer skin of the building help to protect from direct solar gains and reduces glare. Since the shading device within the cavity will also heat up just like the outer and inner skin, the ventilation of the cavity will also help remove heat buildup within these components.

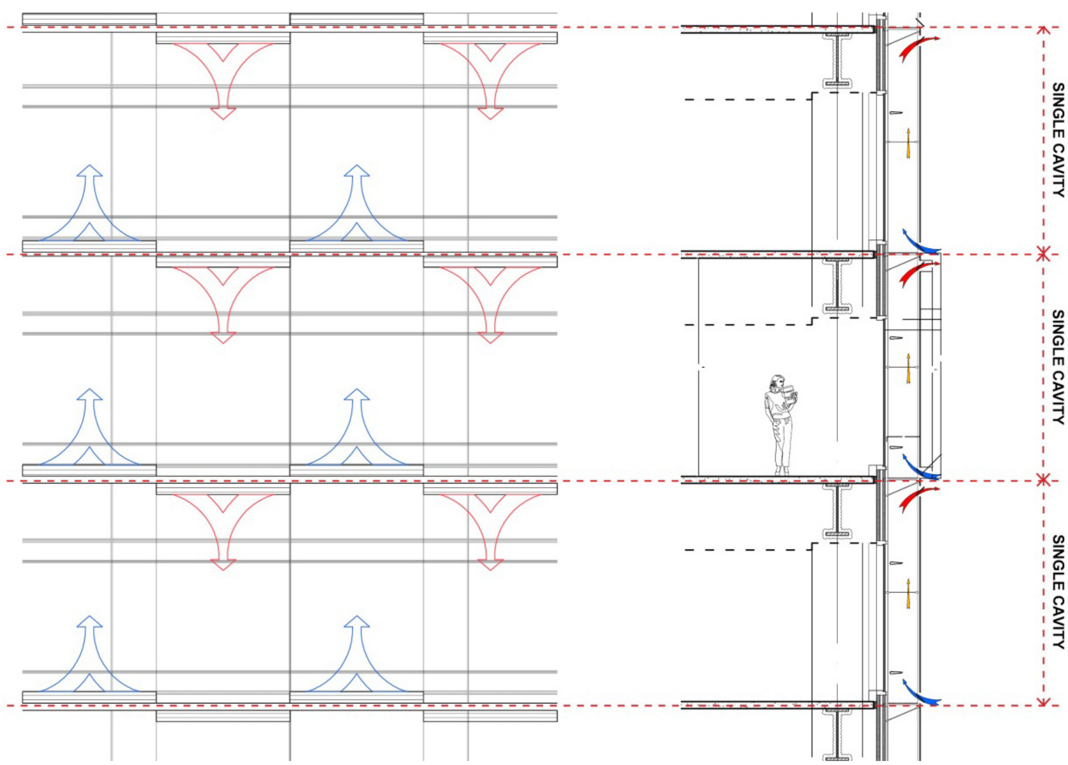


Fig. 3.4: Single story corridor double-skin façade system

CONSTRUCTION

The system consist of two layers of glazing mounted approximately 24 inches apart with the air space between the two layers which is naturally ventilated to and from the outside. The inner skin is comprised of the existing façade system of the studied building (A Low-E IGU curtain wall assembly) where the outer face of the building is entirely clad with high-reflective glazing panels between horizontal bands of aluminum ventilation boxes. The double-skin cavity envelopes each floor creating a perimeter zone between individual floors and is structurally attached to the building via cantilevers.

The design of this system led to the use segmenting the system and forming a 13 foot flue consistent with the floor to floor height of the existing structure. The average U-value of the glazing is 0.855 Btu/h-ft2-^{0}F. With the use of automatically controlled dampers, they provide both air-intake and air-exhaust spaced from bay to bay limiting the thermal buoyancy of the existing system.

The following diagram begins to break down the composition of the single story scenario and locates the specific components of the final façade composition upon the existing façade.

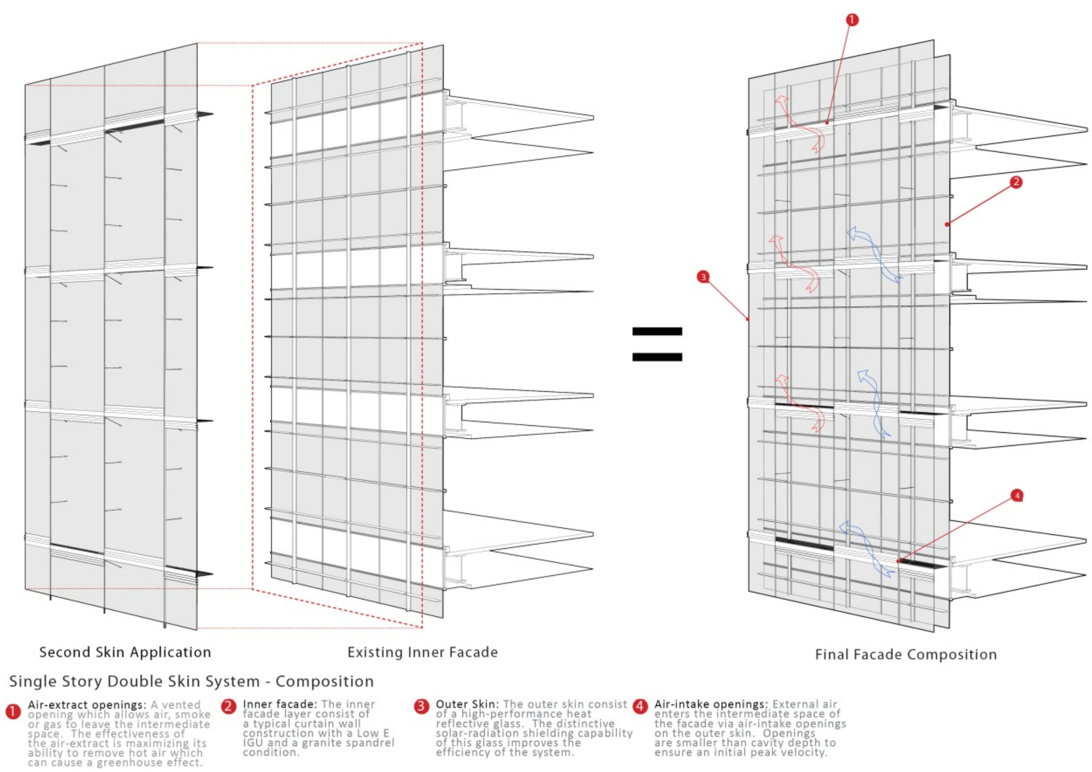


Fig. 3.5: Single story system layer composition.

ENERGY FLOW PATH

Simulation of the design scenario has revealed the specific heat balance and temperature of the system. Using the graphs below, we can analyze this specific system and how it affects the buildings internal temperature and those cooling loads needed to provide a comfortable interior environment. Like the previous scenario, the amount of temperature that is transferred into the cavity space is relative to the specific material selection as noted in the previous section. The heat balance graph (gains breakdown) maps heat gains and losses within the existing cavity condition. These include solar gains from exterior windows (outer skin), solar gains on interior windows (inner skin), glazing, partitions, zone sensible cooling and external air ventilation indicated by the colors shown in the legend. The zone temperature graphs map the operative temperature, air temperature, radiant temperature and the outside dry-bulb temperature. The following section is again presented as two parts; the graphs shows individual breakdowns which are measured in kBtu/h and temperature by ^{0}F for the specific boundary condition of both the cavity and the adjacent occupied space.

<u>Cavity Zone</u>

When looking at the temperature graph of the specified cavity zone, we can see that the radiant temperature of the space is the highest value. The mean radiant temperature is expressed as the surface temperature of the surrounding system within this zone, dependent on surface emissivity. This level of radiant temperature is due to the high levels of solar gains on the exterior window of the second skin. Nonetheless, the air temperature of the zone is relatively identical to the ambient air temperature of the surrounding environment. This condition is evident because the system is has openings to the exterior environment, thus allowing the ambient air temperature to ender the space creating a direct link in air temperatures. When looking at the operative temperature of the system (green) this represents a balancing of the system between the air temperature and the uniform temperature as an exchange of heat by the radiation temperature and the air temperature within the cavity to create the total relative temperature of the cavity space. The temperature ranges for each specific value can be seen in the graph on an hourly value over the course of the specified summer design week.

Looking at the heat balance of the cavity zone, we can see that the external solar gains from the glazing system account for the largest amount of energy peaking at 3 kBtu/h during noon throughout the week. When looking at the solar gains on the interior skin, we can see that there is a considerable low value thus indicating that there is a large reduction in solar gains from the exterior to interior skin. An interesting variable that identifies a negative value in the system or heat loss (cooling) is the external air infiltration. The natural ventilation of the system actually causes the energy flow of the system to be reduced. The numbers of the specific temperatures and the heat gains and losses of the system can be seen in more detail within the graph. With an understanding of the energy flow within the cavity space we can begin to understand how it will affect the adjacent occupied space within the next section.

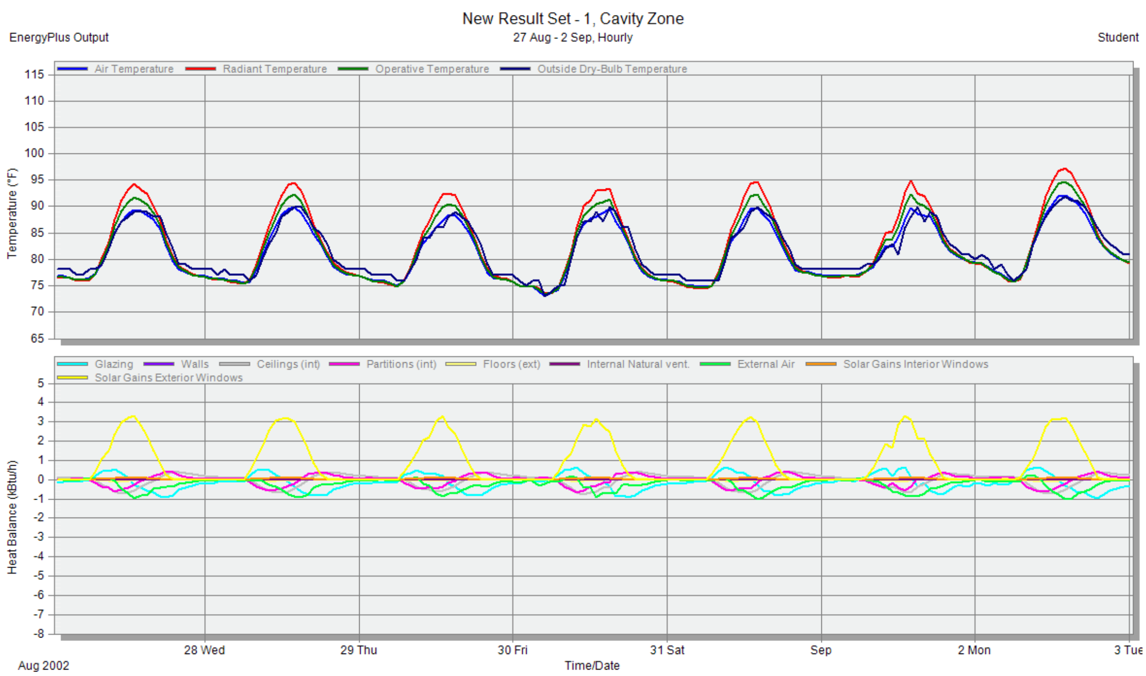


Fig. 3.6: Energy simulation of cavity zone.

Occupied Zone

When looking at the occupied zone of this specific design scenario, we can really see and understand how the cavity space has affected the interior temperature and heat balance of the system. Since the interior space has been specified as mechanically conditioned, the operative temperature has a set point of 75.2^{o}F. As a result, when looking at the system loads graph we can see the total amount of sensible cooling for the specified boundary condition. The goal of this study is to help reduce the total amount of system loads with the addition of a second skin to the existing façade system. Currently the max load on the cooling system is -5 kBtu/h during the hours when glazing gains are the highest.

Looking closely at the heat balance of the system and breaking down the specific gains that effect the system the most, we can see that the glazing has a considerable effect of the overall balance of the system, however it is the miscellaneous category that makes up the highest interior gains. These miscellaneous values are the effect of the occupancy loads on the system and show that during the lunch hours of the day the load deceases slightly. Again, during the weekend the system loads are turned off and there are no occupants within the building thus representing a zero value on the graph.

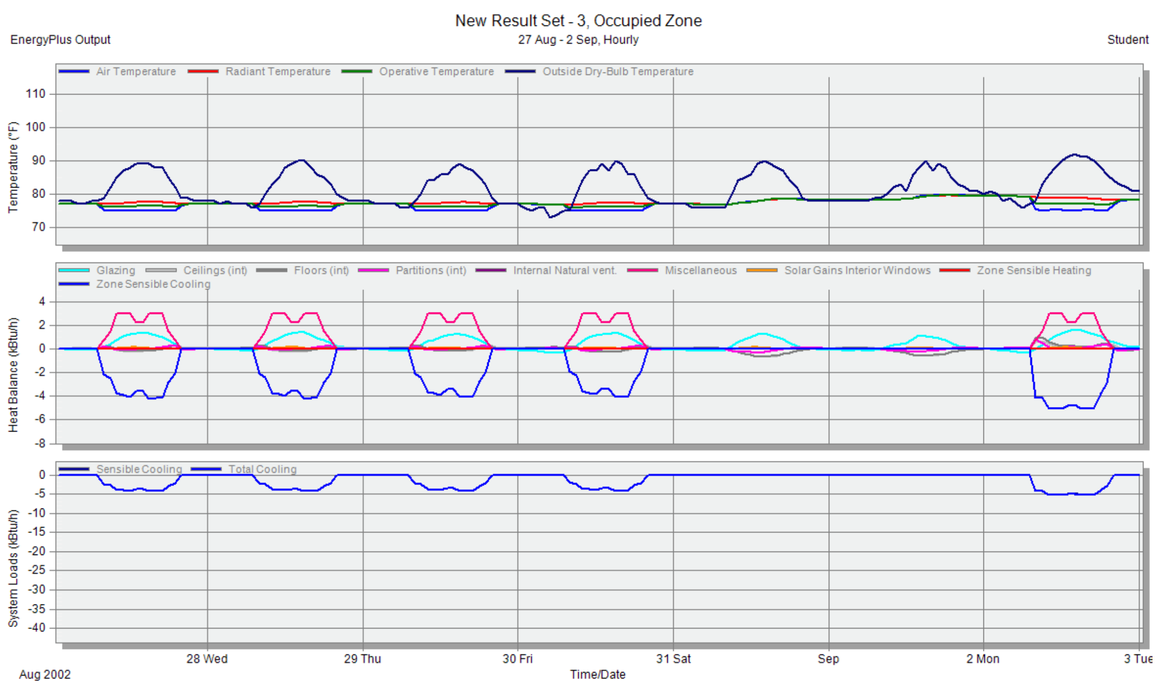


Fig. 3.7: Energy simulation of occupied zone.

AIR FLOW PATH

Compared to the previous multi-story façade, the single story cavity will present other challenges when it comes to maximizing the air flow paths within the system. The ventilation of the intermediate space involves questions relating to the velocity of air flow, the temperature distribution within the air temperature and the pressure differences that are always the motive force of air currents. The relevant air flow patterns for this specific scenario can be largely determined on the basis of the information contained in the CFD simulation results concerning the ventilation of the facades intermediate space.

Velocity & Pressure

The ventilation of the system is delivered through an 8 inch opening at the top and bottom of the cavity. The intake and exhaust vents are staggered as stated previously so that the hot air being extracted from the previous floor will not enter the intake of the exceeding system. In this case, the driving force has been divided into two intake vents at about 228 ft3/min totaling at an overall mass balance of 456 ft3/min. This is considerably less that the multi-story condition because there is a smaller area open to the exterior. This lower amount of air flow within the system can be seen with the lower max velocity within the cavity space.

As you can see from the above diagram, the various velocities of the air within the system are largely impacted with the location of the intake and extract vents. All of the vents have a relatively high flow rate of about 53 ft/min compared to the areas within the system that ventilation is considerably low. The staggering of the intake and outtake affects the ventilation efficiency of the system and does not create a laminar flow but rather one that is highly turbulent, creating eddies throughout the system. As for the sectional study of the velocity within the system, the negative pressure at the intake of the cavity creates a high velocity of air flow but again, due to the nonlinear arrangement of the openings, a continuous streamline of air flow is lacking. It is interesting to note that the staggered effect to prevent hot air transfer between floors also have an effect on the specific flow within the system as illustrated within the above diagram.

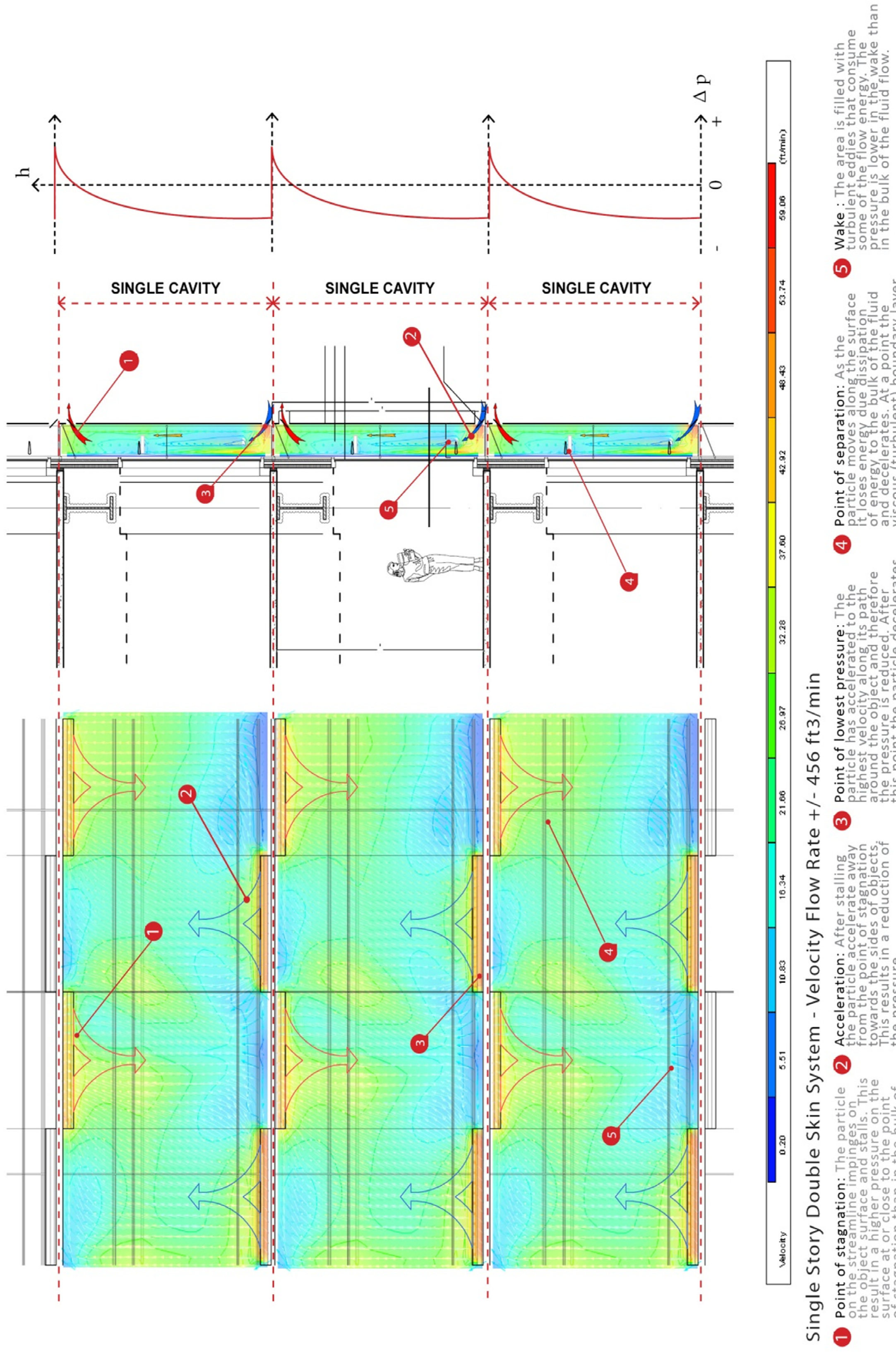


Fig. 3.8: CFD of single story velocity flow rates.

Temperature Distribution

Looking at the results from the CFD simulation on temperature distribution, we can see that the external ambient air entering the system is around 86^{o}F and the maximum air temperature within the cavity is 90^{0}F in those areas where stagnant air is trapped due to the staggering of the external vents. This temperature difference between the intake and max air temperature represents a delta T of 4^{0}F. There is less of a temperature difference with in internal space as compared to the multi-story scenario and this has resulted in less thermal buoyancy resulting in lower velocities as stated in the previous section. In this scenario we can see that the temperature distribution within the system is not a constant gradient and results in definite hot spots and wakes with turbulent eddies that consume some of the flow velocity within the cavity space. With this specific system it easy to see how the necessity of staggering the air-intake and the air-outtake to prevent unwanted exhaust heat entering the system above can cause considerable problems when providing fluid airflow within the system. With these results, we can see that these conditions can cause considerable overheating problems where fluid streamlines are lacking. However, as indicated in the simulation, the average zone air temperature within the cavity space is about 87.26^{0}F which is 1^{0}F higher than the external ambient air temperature.

Understanding the temperature curves of the assembly we can begin to identify the specific temperature differences between ambient external air, intermediate air temperature, and internal temperature along with the surface temperature of each layer within the system.

The following diagram helps to illustrate the temperature distribution within this existing double-skin cavity and begins to identify specific temperature readings when it comes to detecting where the maximum temperature, the minimum temperature, and mean temperature of the system as well at temperature curve in a double-skin facade.

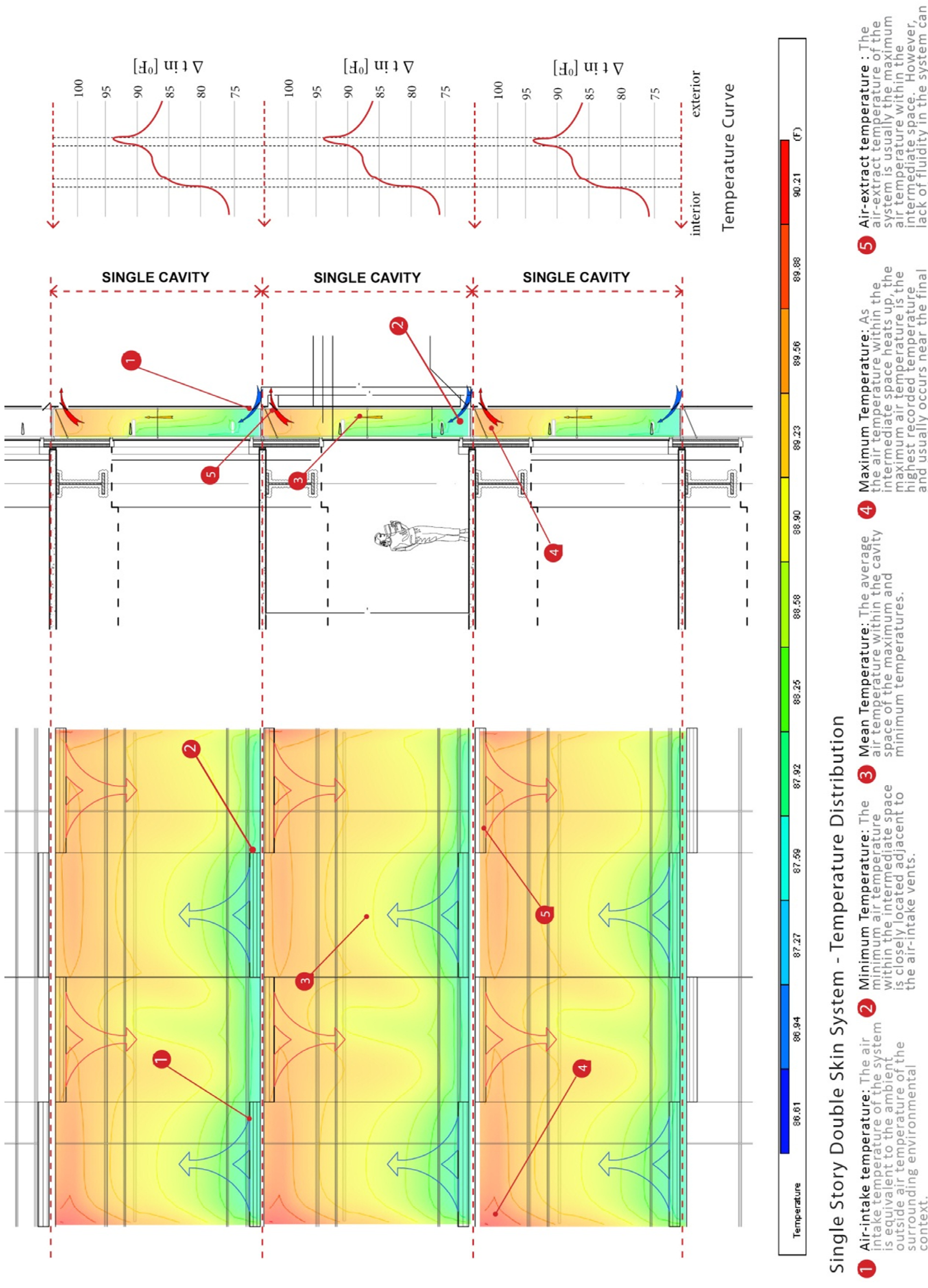


Fig. 3.9: CFD of single story temperature distribution.

3.3.2. Scenario 2 – Multi Story

The multi-story façade scenario consists of an external air curtain where the air cavity is open at the top and bottom, forming a large open volume. The intermediate space between the inner and outer layer is joined vertically and horizontally by a selected number of rooms. This double-skin system assists in providing energy efficiency and comfort in the building. An external air curtain is formed by a single high-reflective glazed skin 24 inches from the inner double glazed façade. Air flow into the flue and out the top is regulated via dampers controlled by the building management system. When external air temperatures rise, the dampers are opened to allow the ventilation of the intermediate space to prevent it from overheating. The air curtain creates an airflow that is projected over the inner façade of the building. This curtain acts as an invisible layer which separates climate controlled interior air from outside temperatures. As a rule, the rooms behind multistory facades have to be mechanically ventilated, and the façade can be used as an air buffer for this purpose.

A central aspect of the concept is a low energy strategy with the addition of a second protective skin and constant ventilation of the intermediate space. One of the major components of the double wall is that it acts as a weather screen, providing protection against heat gain and a thermal flue which promotes ventilation in calm weather. Insulation values are relatively high, including the glazing on the outer skin. High energy loads generated for cooling comfort can be minimized by the implementation of this façade system. It is quite common that this system can be used as an addition to a building and makes it possible to reduce the load on the systems of the building.

The brief was to provide an added layer of protection while minimizing its impact on the existing façade structure. Focus is placed on the multi-story construction system that is a common construction type for double-skin facades. The following section will describe the specific construction techniques and energy strategies used within this system as well as provide simulations aiming at identifying both the energy flow and air flow within this type of system. Lastly, observation of the specific qualities of the system will be discussed in terms of its viability within the existing context.

DESIGN STRATGIES

With high external loads, the primary requirement of the system is to provide high levels of solar protection while venting away excess heat buildup within the intermediate space. Is staying consistent with design objectives, no external air is used to naturally ventilate the interior occupied space as this deals with an additional set of complex variables. The cooling necessary of the intermediate space during high summer temperatures is provided by existing external driving forces such as wind, and the stack effect created through the height of the assembly. This ventilation strategy for the façade is an important part of the multi-story concept and the need to avoid excessive heat buildup with a lack of constant air flow. The outer glazing system of the facade provides the buffer needed to protect the interior, as well as forms the solar flue which drives the ventilation when wind speed is low.

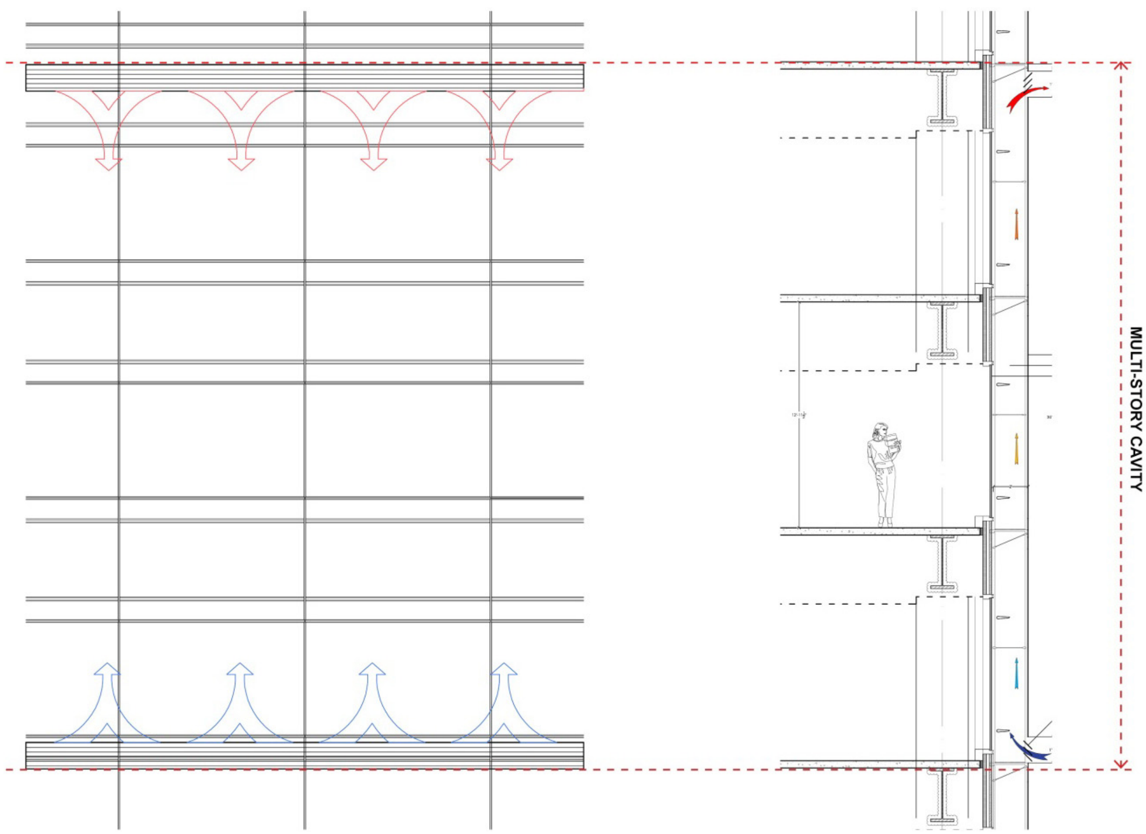


Fig. 3.10: Multi-story corridor double-skin façade system.

CONSTRUCTION

The concept involves separating the second skin from the building using edge cantilevers, minimizing its impact on the existing structure by avoiding heavy reinforced concrete beams. For economic purposes the application of the second skin focuses on maximizing its performance impact while minimizing disturbance of the existing façade. The system consist of a single layer of high-reflectance glazing mounted approximately 24 inches from the existing curtain wall with the air space between the two layers becoming naturally ventilated.

Design objectives led to the adoption of a full glazing extending over three floors. The outer skin forming the flue consists of a highly reflective single glazed glass with aluminum mullions which are thermally broken. The average U-vale of the glazing is 0.855 Btu/h-ft2-^{0}F. Mechanically controlled dampers provide both air-intake and air-exhaust spaced every three stories and form the height limit of the existing system.

The following diagram begins to break down the composition of the multi-story scenario and identifies specific components of the final façade composition with the addition of the second skin application upon the existing façade.

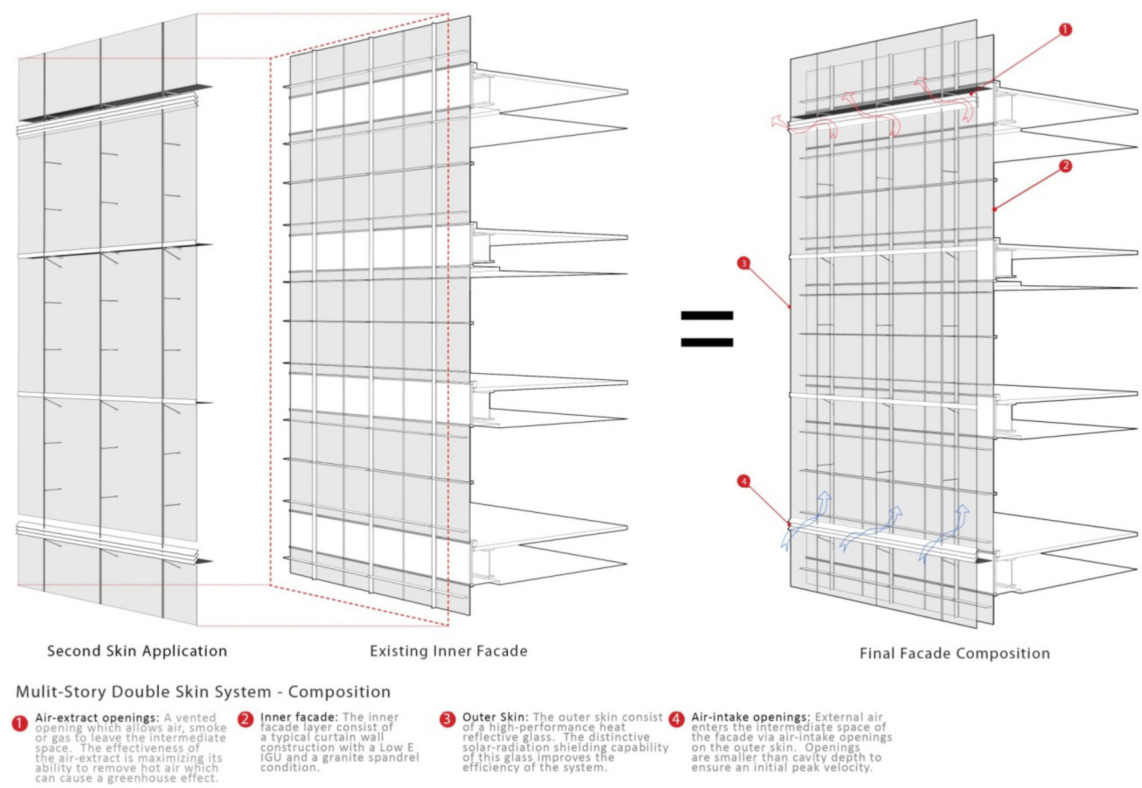


Fig. 3.11: Multi-story system layer composition.

ENERGY FLOW PATH

By simulating the design scenarios heat balance and temperature we can begin to understand its specific contribution to the building internal temperature and cooling requirements. The amount of temperature that is transferred into the cavity space is relative to the specific material selection as noted in the previous section. The heat balance graph (gains breakdown) maps heat gains and losses within the existing cavity condition. These include solar gains from exterior windows (outer skin), solar gains on interior windows (inner skin), glazing, partitions, zone sensible cooling and external air ventilation indicated by the colors shown in the legend. The zone temperature graphs map the operative temperature, air temperature, radiant temperature and the outside dry-bulb temperature. The following section is presented as two parts; the graphs shows individual breakdowns which are measured in kBtu/h and temperature by ^{0}F for the specific boundary condition of both the cavity and occupied space. When breaking down the graph we can see the gains and losses of each individual zone and how they affect the one another. It is important to be aware when comparing the results between the different gains breakdown and how each individual gain and loss affect each other's overall performance.

Cavity Zone

Looking at the cavity heat balance graph, we can see that solar gains from the exterior skin represent the largest value at an average of 13 kBtu/h at noon during the selected summer design week. The light blue line indicates that the existing inner skin slightly reacts to this heat gain, however during the afternoon hours there is heat loss of -4 kBtu/h which accounts for thermal loss from the interior space. The green line represents the external air change (ventilation) of the system and its effect on reducing the heat gain that enters the cavity space. As we can see from the graph, the external air creates a cooling contribution from the external vent airflow. The pink partition line represents the heat gain and loss of the internal skin through its opaque surfaces. Looking at the heat balance of the cavity space as a whole we can see that there is a large buildup of heat gain that will be evident. The heat losses of the system are an effect on heat transfer from the natural ventilation of the cavity as well as the cooling loads of the interior occupied space. By looking at the graph we can see that the system is not at thermal equilibrium in the space, where the heat gains are higher than the heat losses.

The temperature of the cavity space can be seen on the represented graph below. As illustrated on the graph, the radiant temperature within the cavity space is considerably large as we can see from the previous heat balance graph where we identified a high level of solar gains. This is a direct correlation between the two; a high solar gain represents a high radiant temperature. In contrast, the air temperature within the cavity space is identical to the outside dry-bulb temperature. This shows us that the natural ventilation of external air in the zone that was a heat loss in the previous graph has helped to balance out the temperature of the cavity space resulting in an air temperature proportional to the outside ambient air temperature.

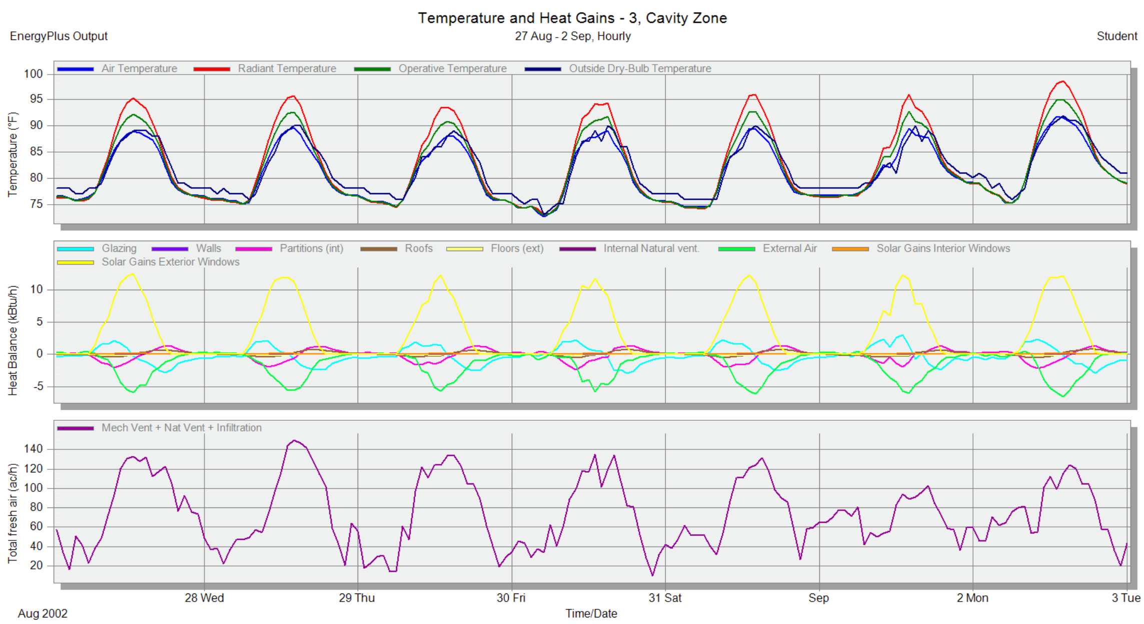


Fig. 3.12: Energy simulation of cavity zone.

Occupied Zone

Looking at the occupied heat balance graph, we can see there is considerably less heat gains and losses within the system. However, the zone sensible heating represents the largest load when it comes to balancing the system. During the summer design week we can see that the total cooling of the occupied space represents and average of -5 kBtu/h during peak hours of the day. This illustrates that the heat gain from the cavity space is also affecting the internal cooling loads of the occupied zone. Glazing, partitions, solar gains and miscellaneous (occupancy) all have to be offset by the sensible cooling. Because the occupancy and schedule of the HVAC system is set to only be on during working business hours, the graph shows that from 8:00pm to 7:00am and during the weekends that the cooling load is at 0 kBtu/h. It is also interesting to note that on the following Monday, the system has the largest daily load due to the lack of cooling and excessive heat gain through the cavity during the weekends.

The temperature within the occupied zone stays fairly constant as the operative temperatures within the zone have been set to provide cooling set point temperature at 75.2 ^{0}F. The cooling set point temperature requirements are related to the generic office area activity within the zone. The cooling loads that are needed in order to provide this condition within the room can be seen in the zone sensible cooling within the previous graph. This is evident with the heat balance of the zone and the amount of zone sensible cooling used to offset heat gains that create heat buildup. These numbers also represent the total cooling loads of the system and thus need to be understood as this will greatly affect the overall thermal and energy performance of the system.

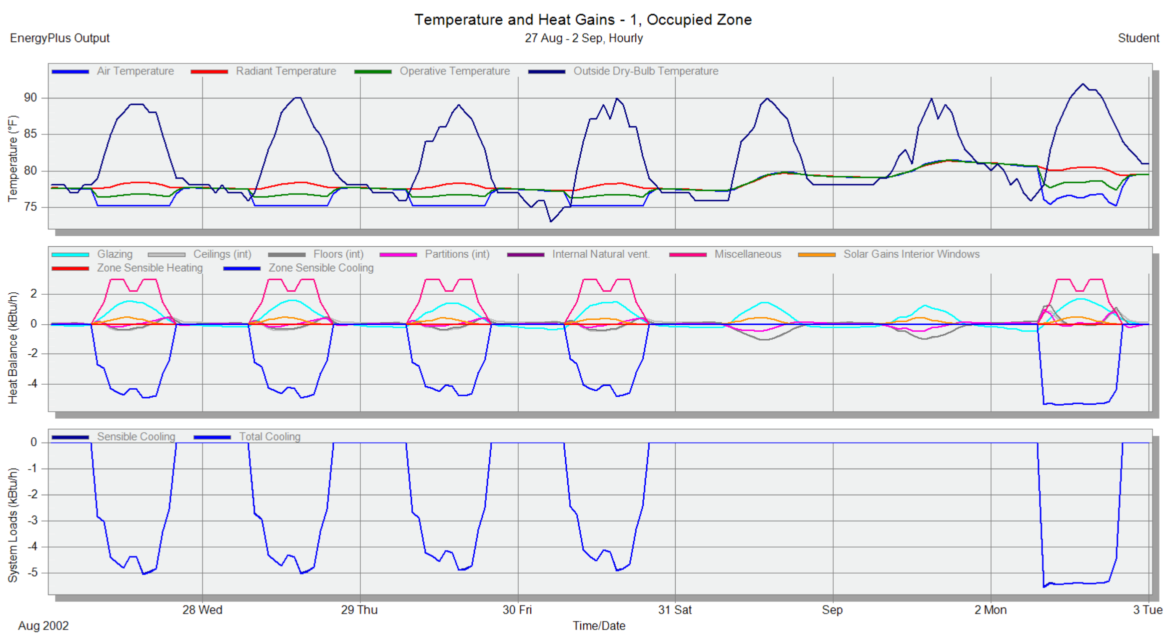


Fig. 3.13: Energy simulation of occupied zone.

AIR FLOW PATH

The allowed height of partitions depends on cavity sizing; however, the upper limit is given by the allowed air temperature rise in the cavity as air temperatures increases relative to the height of the cavity. The ventilation of the intermediate space involves questions relating to the velocity of air flow, the temperature distribution within the air temperature and the pressure differences that are always the motive force of air currents. The relevant air flow patterns for this specific scenario can be largely determined on the basis of the information contained in the CFD simulation results concerning the ventilation of the facades intermediate space.

Velocity & Pressure

In order to identify the relationship between pressure and velocity we need to understand the streamlines of the system. The flow within the cavity accounts for the shading devices that create losses and affect flow path and pressure. In this design scenario there is a large 1 ft. opening at the bottom of the systems which represents the intake of fresh ambient air. The driving force of this opening is around 4700 ft3/min as calculated by EnergyPlus. The velocity of the air within the cavity space is a combination of both natural driving forces plus the stack effect created from the surface temperatures of the assemblies. The pressure differences between the upper and lower openings is the product of the system pushing air through the opening to equalize through flow of air so that an equilibrium of air flow is achieved. As we can see, the average velocity of the system is at 175 ft/min. However, where there are the shading devices there is an increase in turbulence of the air flow and causes pressure differentials which decrease the velocity. The following diagram illustrates the specific velocity vectors and contours within the cavity space. The wall section shows that towards the outer skin of the façade, the air velocity is at its max where there is less turbulence. In contrast, where the existing shading devices are located one can see that there is a higher air pressure which decreases the air velocity. The overall magnitude of the airstream is the product of the motive pressure differences and the resistances of the internal objects that define the air speed and air movement throughout the space. The motive pressure differences responsible for thermal uplift also add to the overall air velocity within the cavity space.

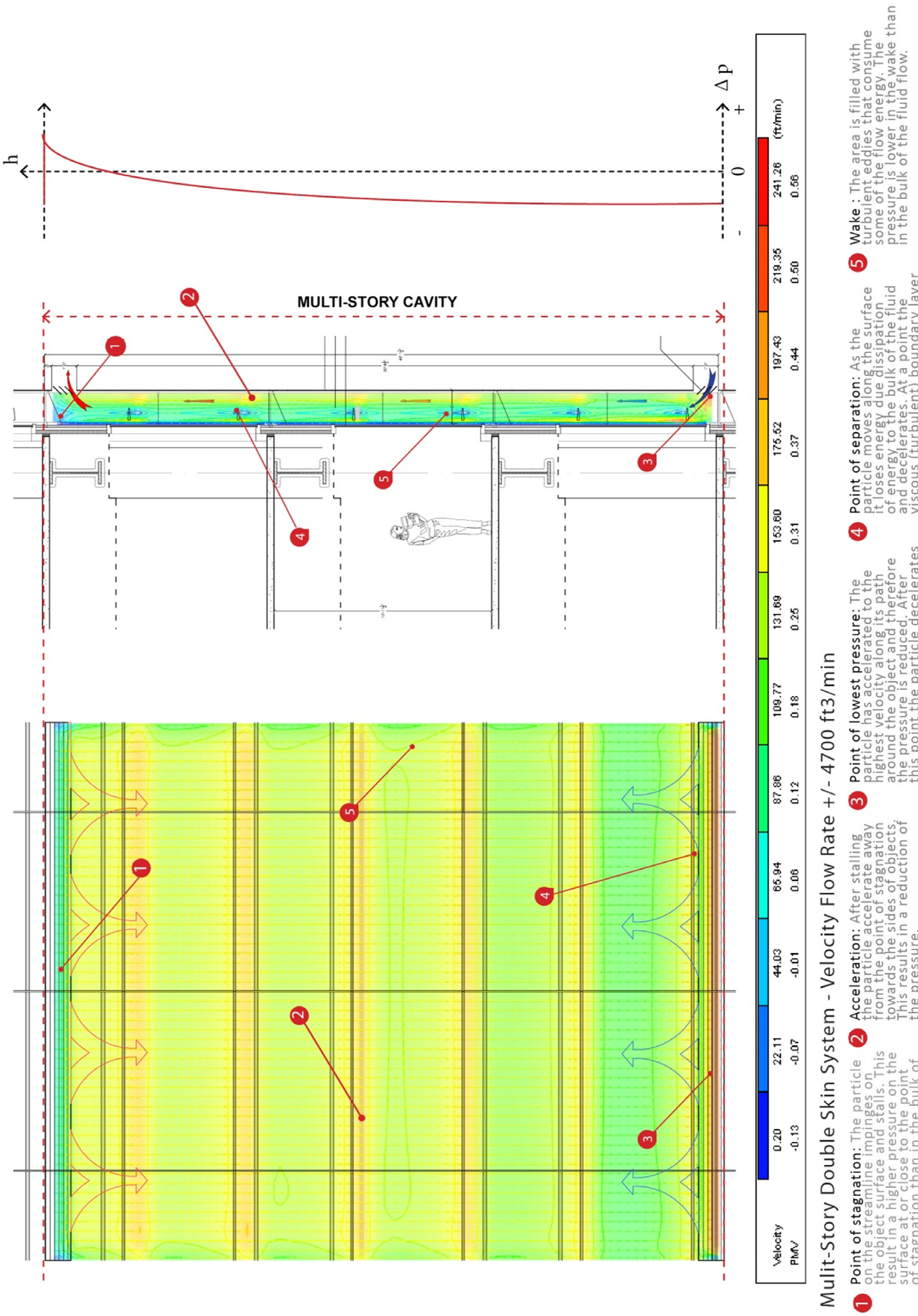


Fig. 3.14: CFD of multi-story velocity flow rates.

Temperature Distribution

As shown in the following diagram, the external ambient temperature entering the cavity is around 86^{o}F and the maximum air temperature rise in the cavity is 95^{o}F before it gets released through the air extract opening on the outer skin. With the specified height in the intermediate space spanning three stories the temperature change within the cavity has a delta T of 10^{o}F. It is easy to see that with an increase in height of the cavity space, the higher the air temperature will be. However, with the increase in temperature, the greater the thermal uplift (stack effect) hence the increased velocity of the air flow mentioned in the previous section. In this specific scenario, we can clearly see that the temperature distribution of the system within the diagrams with the even gradation of color from dark blue to red. Because the air temperature within the designed system increases greatly over the height of the cavity, it is important to reduce the higher levels of air temperature by increasing the velocity within the system. However, the average zone temperature of the cavity space is 89^{0}F as indicated by the energy flow simulation. It is important to note that the temperature distribution of the system is highly dependent on the specific material choice of the outer skin as well as the amount of air movement that is occurring. In contrast, this system may not be viable if there is not enough air distribution within the system. Lack of ventilation will lead to an excessive amount of heat buildup and would make the system actually impair the current building condition and cause a considerable increase in the amount of cooling loads required within the occupied space.

The following diagram illustrates the temperature distribution within the double-skin cavity and begins to identify specific temperature readings when it comes to detecting where the maximum temperature, the minimum temperature, and mean temperature of the system.

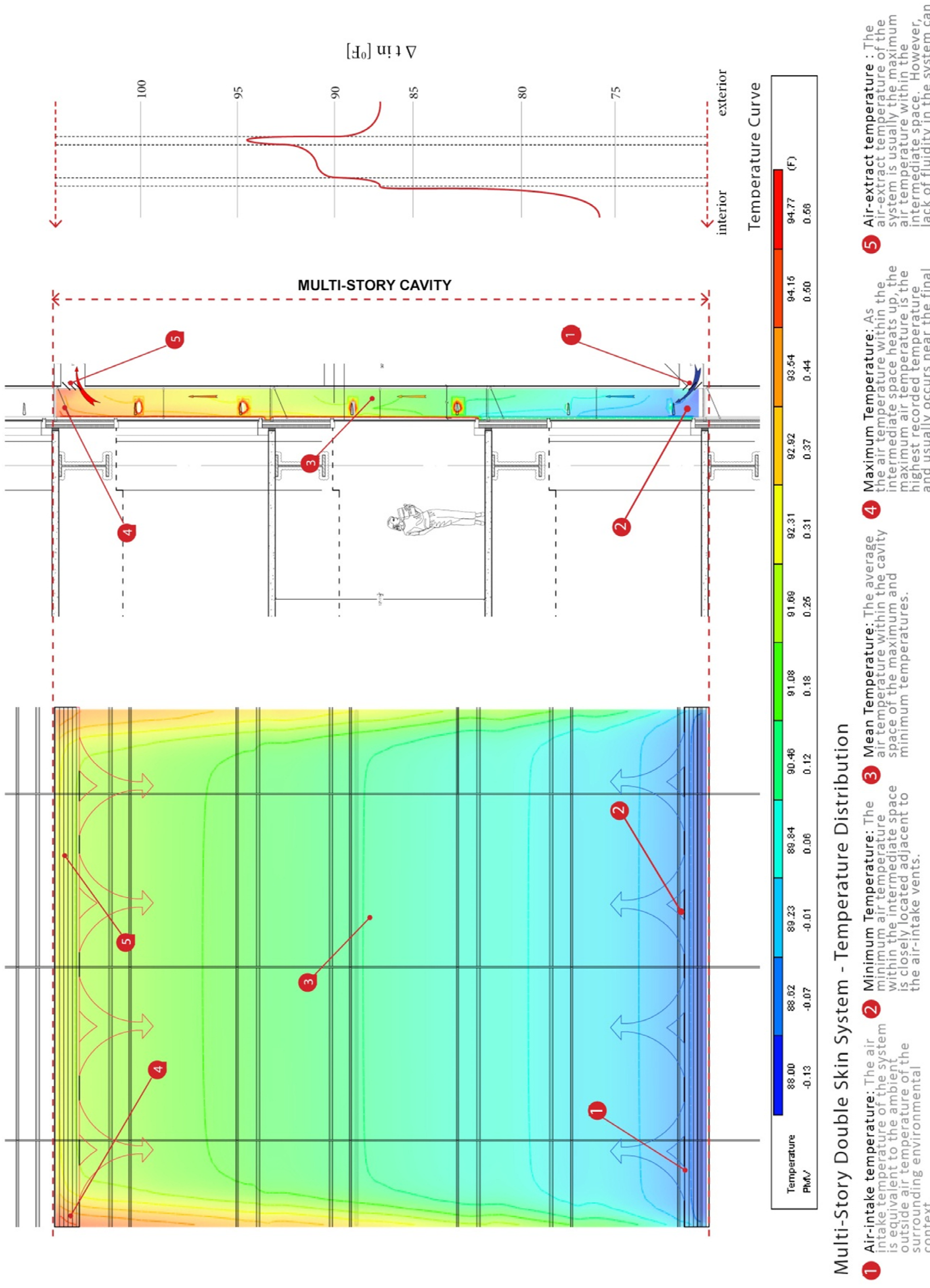


Fig.3.15: CFD of multi-story temperature distribution.

3.3.3. Scenario 3 - Hybrid

The hybrid façade scenario consists of a double-skin façade system with operable panels that can open or close according to the needs of the system. With this hybrid system a single story or multi-story condition can be formed by means of opening and closing each individual panel accordingly. In addition, multiple variations across the height and width of the facade can also be possible to allow for an even more flexible system. The overcladding of the existing building with this system seeks to improve thermal and ventilation performance. The new glazed outer skin consists of a three part band of automatically controlled windows, all able to adjust according to solar angles and other various parameters. Just like the other systems, this façade will also help at reducing interior radiation, façade temperatures and increase natural ventilation of the building surface.

The main objective of this system is to take into account both the previous scenarios and combine them in a design that allows for maximum flexibility. With this hybrid system 3 various configurations will be under investigation; a fully vented, a multi-story, and a single story configuration, each with operable panels open at a maximum of 45 degrees. In these three configurations the various scenarios available within this type of system will be identified in terms of thermal and ventilation performance. The benefit of having such a hybrid system is its ability to fully control the amount of shading and ventilation levels of the inner skin. During extremely hot temperatures, the façade can fully open to allow for maximum air flow around the system when wind speeds are present. In contrast, the system will still have the ability to close up to build a thermal buffer and promote a stack effect between the two facades when driving forces are limited.

The brief of this scenario is to study a hybrid façade system that allows for maximum flexibility in terms of facade ventilation. Since this scenario has the opportunity to become quite flexible, three sub-scenarios will be investigated to take into account the possible variations within the system. These scenarios will be a fully open façade, a single height condition as well as a multi-story configuration. This will help to identify the range of possibilities this system may encounter.

DESIGN STRATGIES

One of the major benefits of having a hybrid system that allows for flexible opening ratios and cavity heights is the added control of the air temperature and ventilation of the intermediate space. In a multi-story condition, the system can act much like that of the first scenario by providing an air-inlet and air-outlet by closing off a range of panels throughout the height of the building. In contract, the system would be able to provide a single story scenario by opening those panels within the floor to floor limit as well as variations between the two. In this system, the degree of natural ventilation with operable panels can be adjusted to optimize its buffer performance. However the layout of the system in terms of height differences between intake and outtake are controlled by the maximum allowable air temperature within the intermediate space.

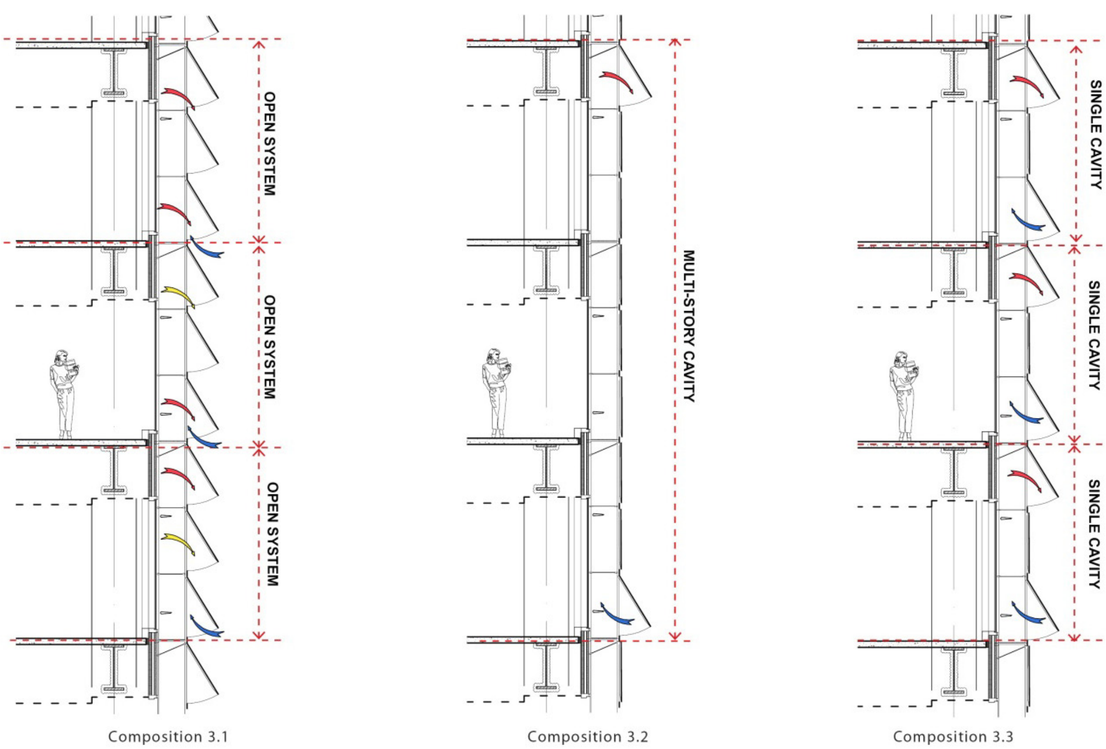


Fig. 3.16: Hybrid façade system composition scenarios.

CONSTRUCTION

The hybrid double-skin façade system comprises of a new framework of high reflectance glazing panels in an aluminum frame. This new glazed outer façade is divided into three horizontal bands of motorized top-hinged window panels at every level, each automatically controlled to perform a different function. These operable bands of glazing panels help to maintain existing views to the exterior and maximum daylight while having the ability to provide and added layer of protection to the existing façade. The individual panels can be adjusted infinitely to a max of 45 degrees as needed. This allows for the system to open and close panels according to the air temperature between the two skins. In extreme summer temperatures, the panels can be fully open. This air movement promoted by the panels helps to cool the inner façade surface and reduce the amount of heat gain entering the building which will ultimately lead to an increased cooling load.

The following diagram begins to break down the composition of the hybrid scenario and identifies specific components of the final façade composition with the addition of the second skin application upon the existing façade.

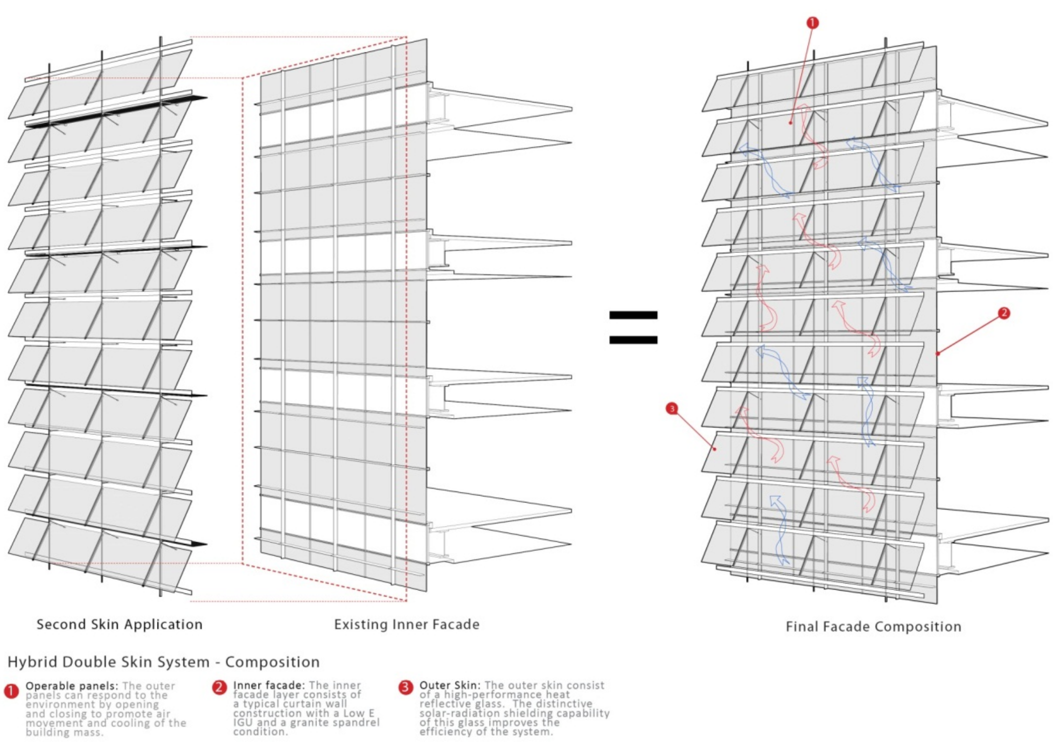


Fig. 3.17: Hybrid system layer composition.

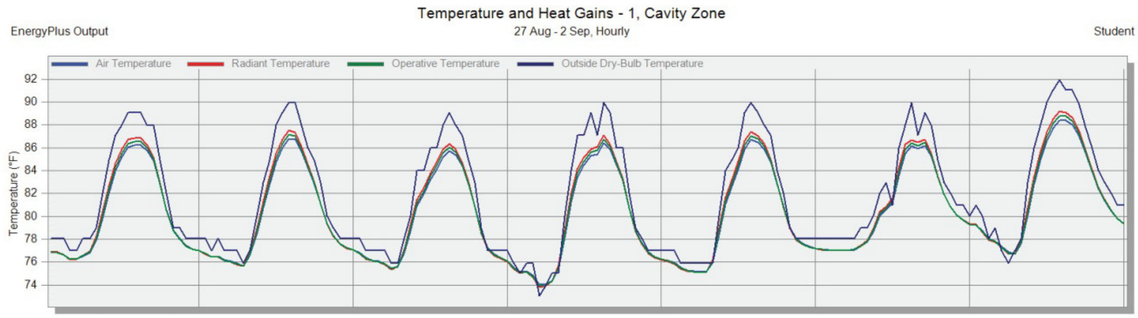
ENERGY FLOW PATHS

Determining the thermal performance of this specific system can be quite challenging due to the possible variations available within the outer façade. However, three scenarios have revealed the specific heat balance and temperature distribution of the system that may be suitable in summer design scenarios. With an understanding of the following graphs of both the cavity and occupied spaces of all three façade configurations, we can begin to analyze the specific temperatures and gains associated within this system and how they ultimately affect the system cooling loads.

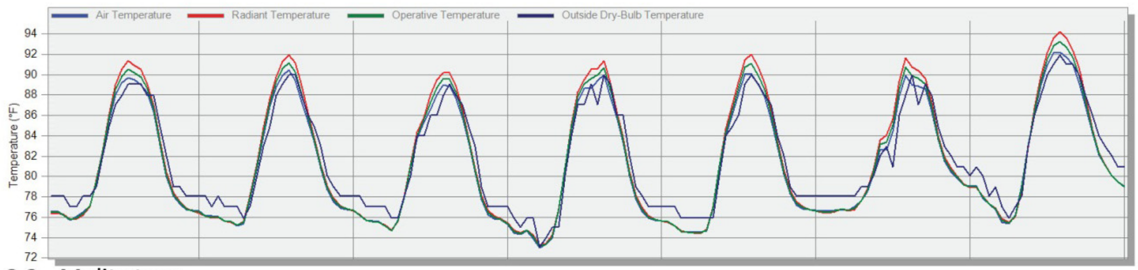
Cavity Zone

Identifying the temperatures and heat gains associated with this design scenario, we can see that from the graph that the operative temperature within the cavity is highly dependent on the variations of the façade configurations. When comparing the difference in operative temperature of the cavity space we can see that the fully ventilated configuration provides significantly lower temperature than the other two. This may be because all the panels are in the fully open position and thus creating a longer distance for radiant temperatures to travel before it strikes the inner façade, thus incrementally lowering its impact on temperature gains. It may also be possible that the fully open panel provide an extra layer of shading on the inner surface as well as providing air movement around the system increasing the convective heat transfer, thus cooling the building mass.

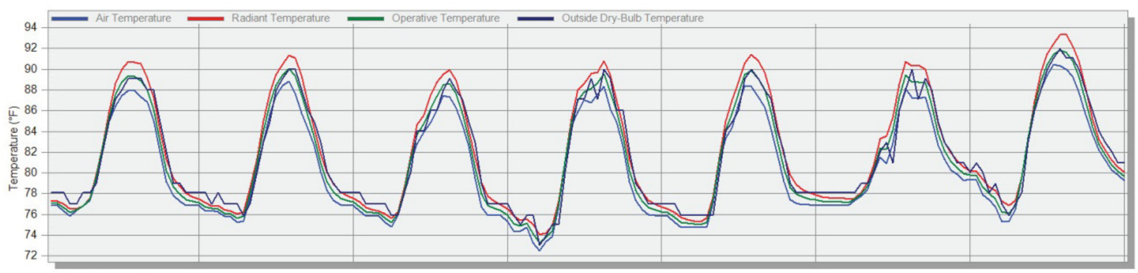
This may be easier to understand when looking at the radiant temperature of each specific configuration as the radiant temperature will ultimately affect the operative temperature within the cavity zone. In the single story façade configuration, the radiant temperature of each cavity zone is around 91^0F. With this temperature combined with the ventilation of outside air temperature the resulting operative temperature is 89^0F. Looking at the three story high cavity section, the operative temperature of the system is relatively higher than any other configurations, indicating that radiant temperature within the system is at high and the amount of exposed glazing is affecting the temperature outcome. As for the fully ventilated façade, the radiant temperature of the cavity is relatively low and thus there is also a relatively low operative temperature.



3.1 - Fully ventilated



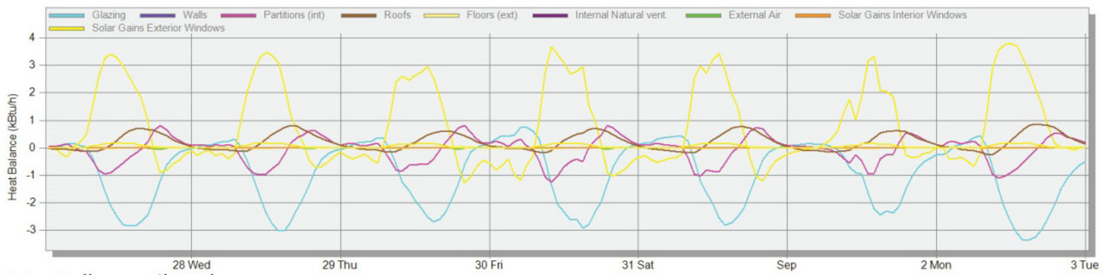
3.2 - Mulit-story



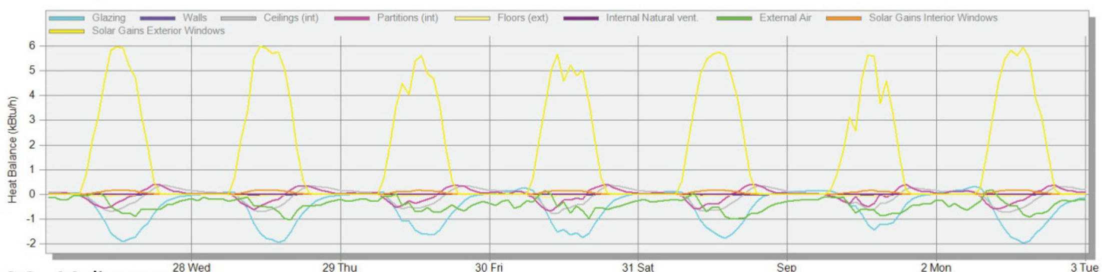
3.3 - Single story

Fig. 3.18: Temperature of cavity zone.

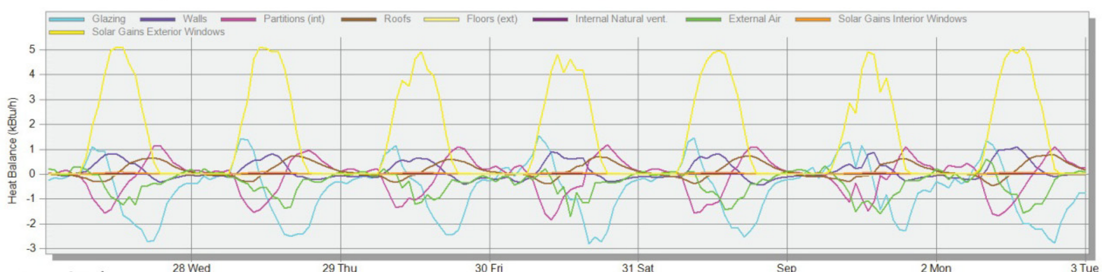
Looking at the heat balance of each configuration we can begin to see some major differences in terms of solar gains. This is due to the level of open and closed surfaces with each scenario and the specified solar gains on those glazing surfaces that are closed and thus closer to the inner layer. As we have seen in the temperature of the fully ventilated system, the solar gains on the exterior windows is significantly less that the other two. This is a result of the fully open configuration of the whole system. This shows that this configuration may be the best system when trying to minimize external solar gains from entering the building. The single story scenario indicates that the solar gains from the exterior façade account for the largest heat gain within this system. However, the internal natural ventilation and external air account for a major cooling component of the intermidiate space. This graph shows how the ventilation of the space creats a negative heat gain within the system and aids in reducing the overall temperature within the system as seen in the previous graph. The multi-story façade configuration has one of the higest solar gains out of all the systems.



3.1 - Fully ventilated



3.2 - Mulit-story



3.3 - Single story

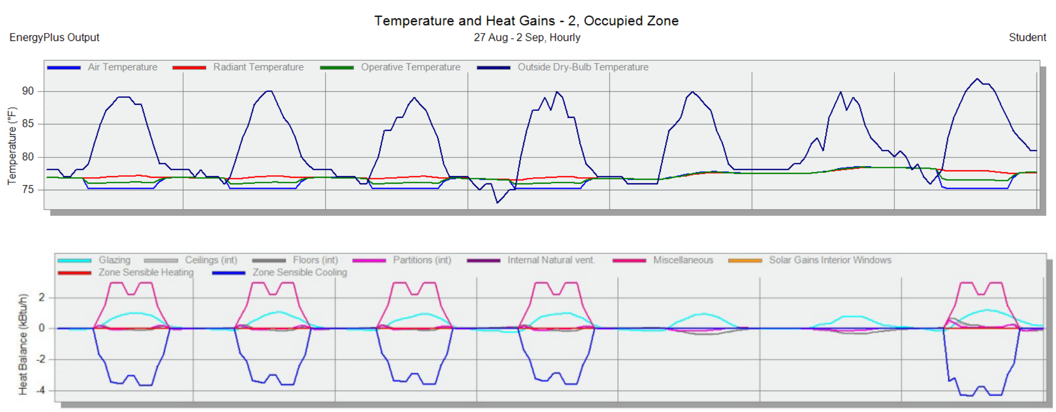
Fig. 3.19: Heat balance of cavity.

With an understanding of the previous graphs we can begin to have an awareness of the specific variations that each specific configuration might have within the cavity. Although these configurations are broken down into separate graphs, the benefits and combination of all three is what makes up the entirety of the hybrid façade. However, the variation of the system will ultimately affect the overall performance and thus should be clearly understood by verifying these results in further detail at a later time.

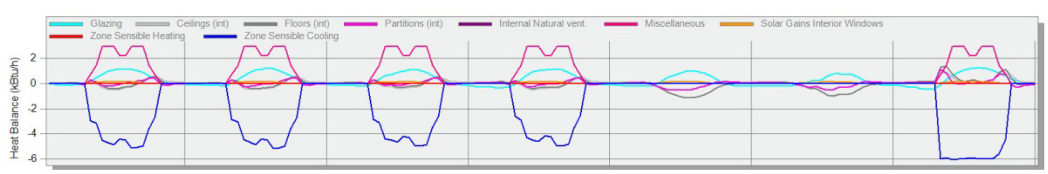
Occupied Zone

The operative temperature within the occupied zone is mechanically conditioned and is set at a specific setback temperature in order to maintain a specific temperature. The specific temperature of the interior space can be seen in the following graph.

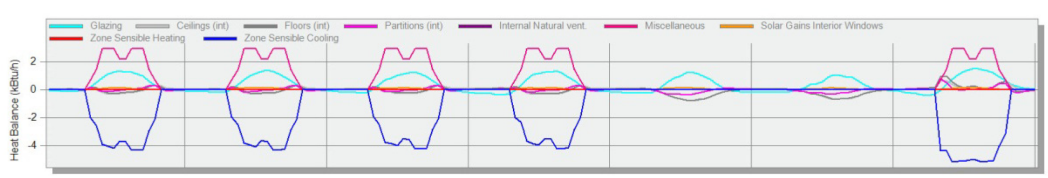
Even through the occupied space has a specific operative temperature; the system cooling loads fluctuate within the different configurations of the façade system. Specific attention should me make on the zone sensible cooling as this is what will ultimately effect the buildings overall system loads in terms of total cooling. One can see that due to the specific effect of external heat gains of the outer surface, the interior system loads have to respond. As predicted, the fully ventilated system has the least loads and the multi-story composition has the maximum.



3.1 - Fully ventilated



3.2 - Mulit-story



3.3 - Single story

Fig. 3.20: Energy simulation of occupied space.

AIR FLOW PATHS

Air flow paths in terms of velocity, pressure and temperature distribution can be quite different within the various configurations the hybrid façade can create. Thus, an understanding of the specific fluid principles that exist in each configuration must be studied. Within the following section, all three configurations are analyzed in order to provide an overall collection and provide insight as to the dynamic ability this façade scenario will have in controlling air movement and temperature within the intermediate space. Although presented separately, it is important to understand the system as a whole and how they affect each other.

Velocity & Pressure

Velocity of air movement within the various configurations depends of the specific pressure differentials each configuration can create. In the following diagram, the three specific variations are studied and specifically look at the wind speeds and pressure of each. By understanding all three configurations one can begin to see how the system may be able to adapt to maximize air velocity through the system depending on the surrounding forces.

The fully ventilated façade proves that with this specific condition the whole depth of the cavity is filled with turbulent eddies that consume a majority of the flow energy. This makes the stream line and specific pressure differentials hard to predict as points of stagnation and acceleration occur throughout various points of the intermediate cavity space. The multi-story cavity resembles similarities to that of the multi-story scenario studied earlier. As the height of the cavity increases, so does the velocity. This may be due to the specific thermal buoyancy of the air within the system creating a stack effect driving air through the system. Acceleration occurs about half way through the height of the system and stays fairly constant until reaching the top. However, due to the specific geometry of the façade the air flow out of the system is not fluid and thus creates a point of stagnation and a turbulence effect. Finally, the single cavity composition illustrates the highest level of wind speeds through the system. A high level of air flow is evident with the brightly colored red filled contours. This system has the least amount of stack effect and may be detrimental when external driving forces are small but may provide effective surface cooling when substantial wind speeds are present. Again, just like that of the multi-story configuration the geometry of the air-exhaust panel proves to be insufficient at maximizing air fluidity though the system and causes considerable losses in velocities and should be considered in future investigations.

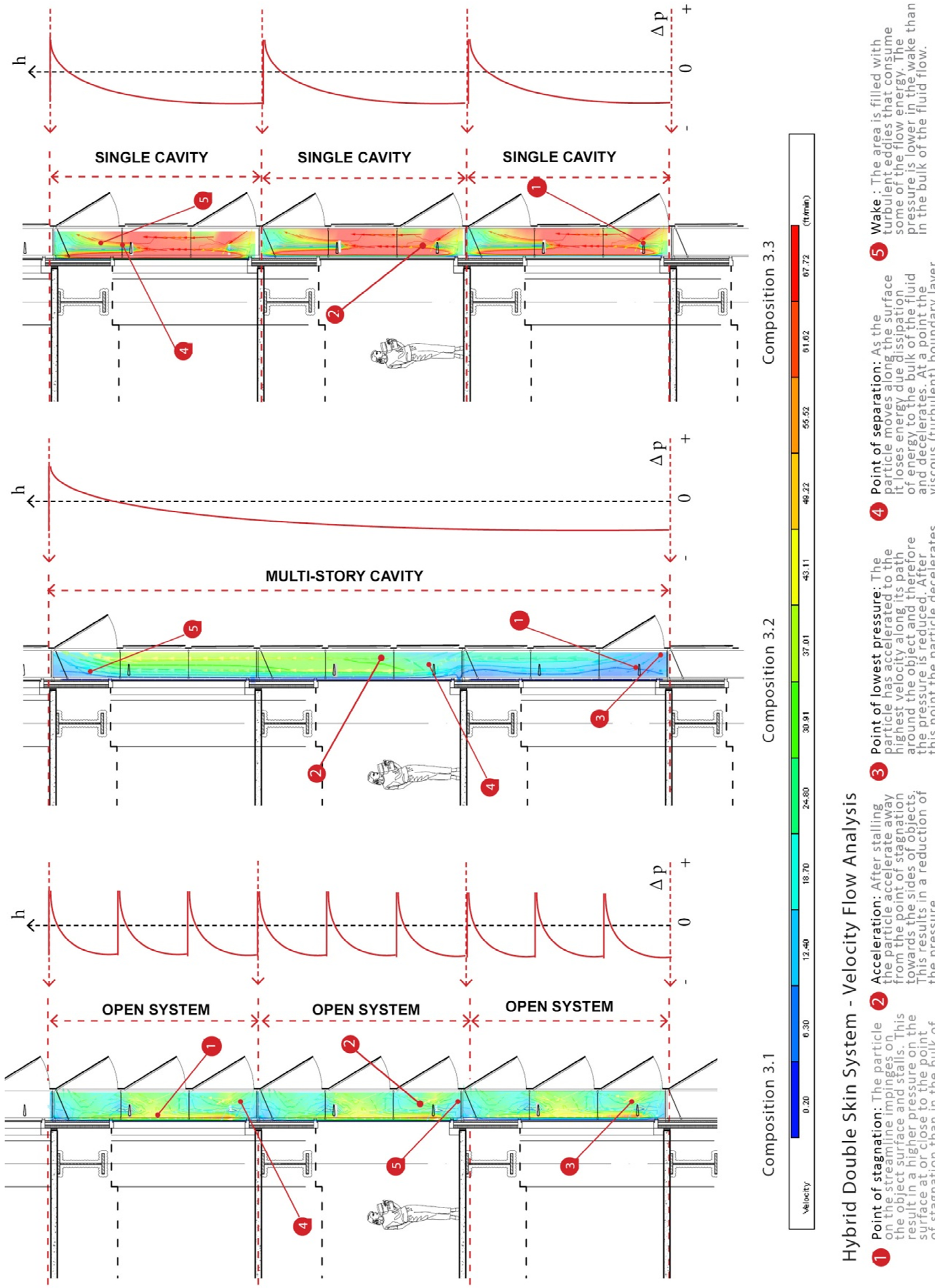


Fig. 3.21: CFD of hybrid velocity flow rates.

The velocity and movement of air flow within the system indicates the speed at which air changes within the cavity will happen. But the temperature differences between air-intake and air-exhaust help to determine how well the system works at creating an interior air temperature similar to that of the external ambient environment. The following diagram illustrates the temperature distribution of each specific composition and their resulting temperature curves. With an understanding of the temperature distribution of each one can begin to comprehend how the system may react within different scenarios.

Within the fully ventilated composition the simulation shows that an average temperature is resulting within the intermediate space. Air temperatures adjacent to the inner façade will reach a maximum temperature of 88^0F within those areas of stagnation stated in the previous section. Due to the fact that this condition is fully open, is it not irrational to see these types of temperature readings. The multi-story composition however reaches a relatively high maximum temperature of 91^0F at the height of the cavity. This represents a temperature change of 4^0F from the intake air temperature. This increase in temperature throughout the height of the three story cavity can cause considerable added loads to the system if not removed effectively. With this increase in temperature there is also an effect on the thermal buoyancy of the system and air velocity. However, the max temperature of the cavity space should be regulated by the allowable height of the system since air temperature will increase accordingly. Thus, careful design of the cavity height is needed when considering the overall configuration of the system. Within the single story cavity composition, the velocity is maximized and the results are evident with the temperature distribution of the system. As seen in the diagram, the majority of the air temperature within the cavity is that of the intake air temperature. Yet at the top of the cavity, the air temperature increases rapidly to a maximum temperature of 91^0F. This may be due to the driving force causing a backdraft of the air-outlet driving hot air back into the intermediate cavity. This is one of the major problems about having this type of top hung panel configurations. In any case this condition can cause considerable system failures and should never be neglected when considering this type of configuration.

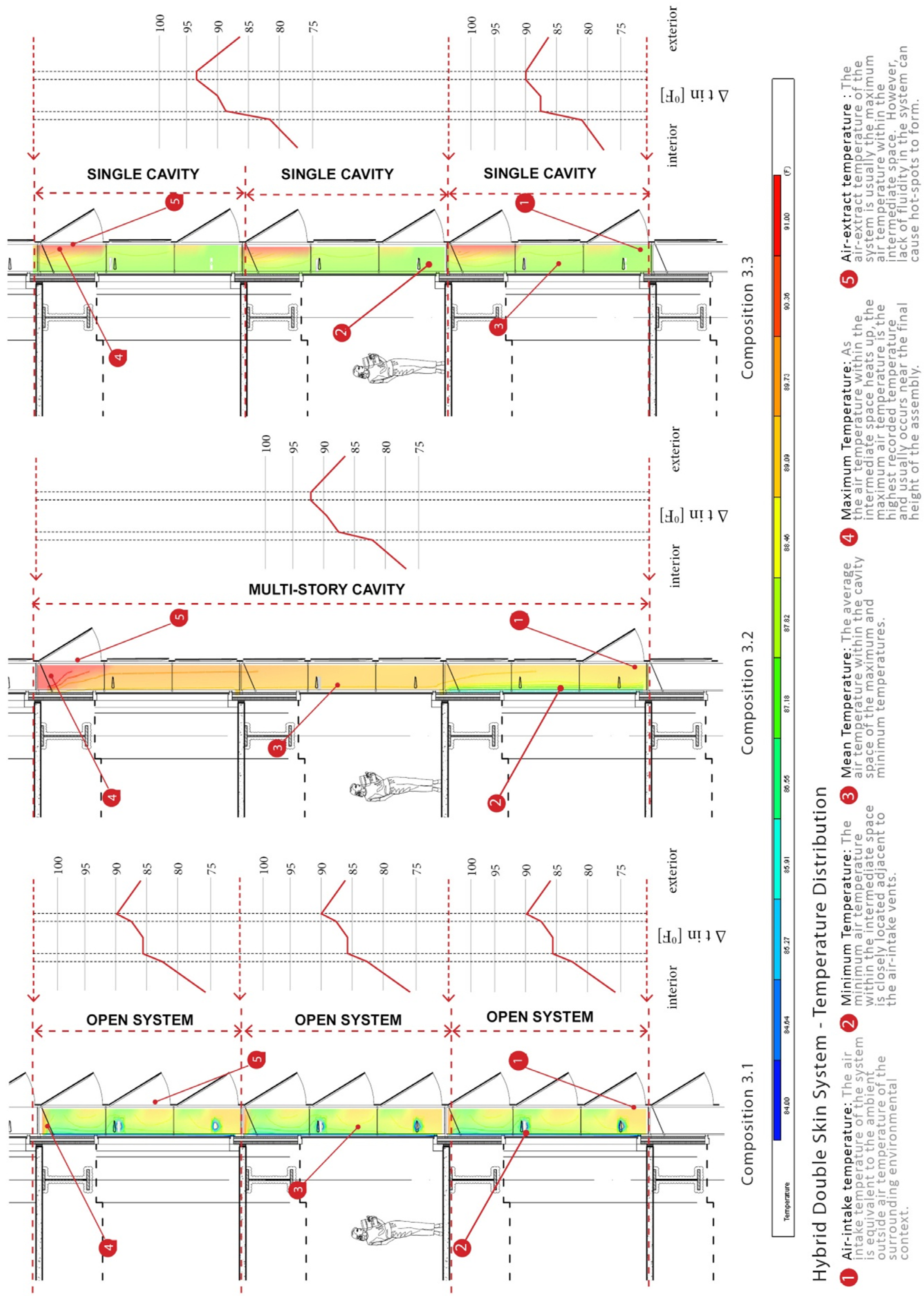


Fig. 3.22: CFD of hybrid temperature distribution.

3.4. Comparative Analysis

Simulations have been performed to understand how each double-skin facade can be used to reduce cooling loads of the building by minimizing thermal gains by providing a level of added performance. By identifying these issues we can begin to understand the specific performance of each individual system and compare them against one another. A comparative façade analysis can help this understanding in identifying the most energy-efficient and effective façade type for the given application. By developing a systematic evaluation of alternative fenestration systems for this project-specific building application, effective analysis and synthesis of the wall systems and investigations on the performance and viability of products and systems can be realized.

The simulation results are presented for the specified boundary study model, therefore a total building simulation must be made in order to give guidance on actual energy savings. However, the results from the studied model show that any type of double-skin wall performs better than the base model for single skin double glazed façade. The presented results could be used to determine which specific system may provide the best overall results.

	Base Model	Scenario 1 (Single story)	Scenario 2 (Multi-story)	Scenario 3 (Hybrid)
January	6923	2521	3624	2260
February	5773	2124	3021	1929
March	6150	2134	2844	2007
April	6349	2128	2645	2201
May	5984	2430	2854	2631
June	6984	2221	2592	2435
July	6272	2856	3287	3105
August	6158	2820	3237	2984
September	6191	2992	3594	2932
October	6957	3300	4116	3059
November	6161	2755	3700	2539
December	6556	2736	3824	2478
Total Loads (kBtu)	**99462**	**31024**	**39343**	**30565**

Fig. 3.23: Total sensible loads of the tested design scenarios.

The results show that any type of double-skin wall performs better than the base model of a single skin double glazed façade. It has been found that the addition of a second layer will reduce the models total cooling loads by 60% but it was the ability for the system to maximize air flow throughout the system and drafting away surface gains is what made the difference. It is indicated that the single cavity height and hybrid model results in lower energy demand than the multi-story scenario since the reduction of maximum air temperature within the intermediate space is reduced in relation to the height of the cavity. However, it is the dynamic model that reduces the total cooling loads of the system the most due to its ability to become fully ventilated, drastically reducing cavity air temperatures by inducing maximum air flow.

It is evident that scenarios with the largest potential to produce ambient air temperatures between the two layers had reduced max temperatures having the lowest enegy demand and heat transfer. By minimizing the cavity height and maximizing velocity of the intermidiate space, significant reductions in energy consumption are observed. In addition, those systems which cretaed the most turbulance decreased the systems ability to streamline airflow and temperature distributions.

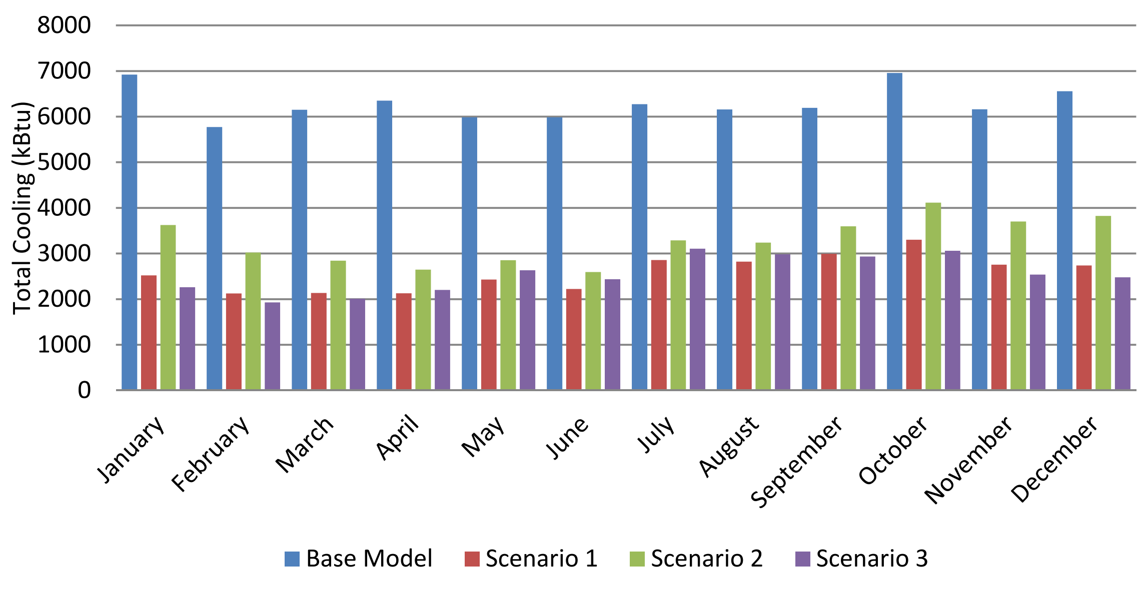


Fig. 3.24: Comparative graph of total system loads.

Based on these results, recommendations for the design of double-skin facades in Hawai`i's climates are:

- *Air cavity*: Limiting the air cavity size reduces cooling loads by minimizing maximum air temperature. However, when external driving forces are limited, a multi-story shaft cavity is needed to produce a pressure difference caused by thermal buoyancy creating a stack effect.

- *Airflow types*: Since majority of the commercial buildings consumed energy is utilized for cooling, there are possible advantages for hybrid ventilation type. Diurnal changes between hot day temperatures and cool night temperatures could also be used, where mechanical ventilation system could be used during the day and natural ventilation during the night. The thermal behavior of double-skin facades is significantly affected by the airflow within the system. The flow of air towards, around and within the assembly greatly affects the overall performance of the system.

- *Shading*: Cavity shading devices can provide some protection against solar heat gain and incorporation of these elements within the cavity is important to the efficiency of the system. All shading devices should be located close to the external skin. However, attention should be placed on the design of cavity shading because if not designed properly, they could create resistance and losses in airflow of the system and will cause an unwanted temperature increase. This relationship is based on a case by case basis in order to obtain the necessary outcome.

- *Glazing*: Effective window sizing and glazing types will have a significant impact on energy consumption. It is important to understand the specifications when selecting an appropriate glazing type. This research has strictly focused on high reflectance glass, however, low-e and high performance glazing may prove to be beneficial within this specific climate context.

IV. CONCLUSION

In this research, different strategies to optimize the thermal performance and energy efficiency of double-skin facades are studied and compared against the results of a base model. By implementing double-skin facades, the performance of all façade scenarios is significantly improved. With the addition of a second skin on the base model, the energy content of the system was useful in lower cooling demand. Using a higher SHGC and reflectance value than transparent glass on the external layer of the double-skin façade offers a first line of defense against the assault of the direct solar radiation in Hawai`i's climate. In this case, the visual continuity between the inside and outside is maintained without interruption from other solid and heavy shading materials that are currently used in buildings within this region. However, the height of the cavity and placement of air-intake and air-exhaust played a significant role in airflow and temperature patterns. Controlling the airflow rate is needed to provide a successful approach to lower the cooling demand for all façade typologies. In most cases, maximizing the ventilation of the intermediate space helped to lower surface temperatures and successfully ventilate heated air away from the building. Ventilation of the air cavity is essential for reducing cooling loads.

The hybrid model has the highest potential to benefit from the optimization techniques. It is able to considerably reduce cooling demand as it has the ability to fully open during hot summer days. The multi-story façade is able to efficiently control the cooling demand but is limited to the specific maximum temperature gained within the cavity space. However, the traditional façade with exterior shading devices may still provide the best solar protection but lacks the ability to actively control façade ventilation. Based on the results of this study, design strategies for Hawai`i's climate that reduce energy consumption include adapting ventilation modes and airflow types to daily temperature change, provide shading devices as well as selecting the appropriate glazing types that decrease cooling loads.

It is very important to understand the performance of the double-skin façade by studying the physics inside the intermediate space. The geometry of the façade influences the air flow, and thus the temperatures, at different heights of the cavity. Different panes and shading devices will result in different physical properties. The interior and exterior openings can influence the type of flow and the air temperatures of the cavity. All together, these parameters determine the use of the double-skin façade and the HVAC strategy that has to be followed in order to successfully improve the indoor environment and reduce the energy use. The individuality of context based façade design is crucial to a high performance solution. It is necessary for the design approach to be comprehensive, considering the facade as an integrated part of the building which is examined in great detail in order to determine all the considerations that will lead to a successful solution. Further research and development are needed within the following:

- Development of advanced CFD techniques used to validate and predict the physical properties of the cavity more accurately.
- Research regarding dynamic intelligent systems.
- Mock up testing of proposed solutions and feedback from real buildings.
- Comparison with external shading device on single skin façade.
- Research on the possibility of multi-layered façade systems.
- Prediction of energy use for entire building.
- Study application.

Design objectives for any façade type are to provide thermal, visual and acoustical performance with minimum energy consumption. Since there are numerous combinations between façade types, ventilation strategies as well as system components, a context based design that adapts to local environment conditions is of primary importance. In a growing context of increased demand in retrofitting and reusing buildings rather than constructing new ones, retrofitting the existing building stock presents the largest potential for the incorporation of energy efficient measures. By understanding the quantitative basis of energy demand in buildings and the impact of the façade with its use, we can begin to implement necessary design solutions. Comparative analysis and simulation of changing façade parameters can provide useful information for façade behavior and assist in optimizing the façades role in creating a high performance building. Energy consumption must be analyzed for the development of any façade and compared for different design scenarios. Design strategies for the building envelope should reflect Hawai`i's conditions without relying on HVAC control systems. This is not a suggestion that avoiding the use of mechanical systems nor that occupant comfort and efficient operation can be individually achieved strictly on the careful design of the buildings envelope. The fundamental premises are that by designing the building's facade to task the environmental control, one can achieve better comfort and efficiency (without operating HVAC systems unnecessarily) for any climate with a well-balanced integrated system rather than a detached curtain wall. Due to the continuous fluctuations of all environmental factors across time, the building façade must be understood not as a simple barrier but rather a selective, permeable membrane with the capacity to admit, filter and/or reject any of these environmental factors.

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2. ILLISTRATIONS

I. INTRODUCTION

II. PROJECT RESEARCH

III. PROJECT INVESTIGATION

Fig. 3.24: Comparative graph of total system loads.

Source: Created by Author

IV. CONCLUSION